ASTRONOMY

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A HANDY MANUAL FOR STUDENTS AND OTHERS

BY

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WITH 95 DIAGRAMS AND ILLUSTRATIONS

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PREFACE

In this little book I have attempted to give an account of the methods employed by astronomers and the reasons for some of the propositions they advance. Astronomical investigations frequently seem complicated owing to the amount of subsidiary detail, but the principles underlying them are simple and usually admit of a clear statement which can be followed by a general reader. In the introduction to his lectures delivered at Ipswich in 1848 Sir George Airy draws attention to an attitude towards Astronomy which is still prevalent. Such questions as the determination of the distance of the Sun or Moon are considered as beyond ordinary comprehension; the instruments with which astronomical measurements are made are supposed to be based on obscure and difficult principles; therefore the best a layman can do is to accept statements on the personal credit of the astronomer making them. He points out that this is an exaggerated view. The principles involved in measuring the distance of the Moon are no more abstruse than those employed to find the distance of a tree on the other side of a river. Astronomical instruments are as simple in principle and far less complicated in detail than a lathe or a steam-engine. It is quite true that in both instruments and methods many subsidiary details must be attended to when great accuracy is required in order that disturbing causes may be allowed for or eliminated. But an explanation of the essential principles may be given which can be readily understood with ordinary care and attention.

As far as possible an historical order has been followed. The reader's attention has been drawn to the desirability of making for himself certain observations of the sky which do not require the use of a telescope. Every educated person ought to see with his own eyes how Sun, Moon, Stars and Planets move in the sky, and be able to infer from his own observations the movement of the Earth about the Sun, the comparative nearness of the Moon, and other commonplaces of Astronomy.

It is difficult to acknowledge fully my obligations to the authors of books and papers which I have consulted. Mention should be specially made of Mr. Arthur Berry's *History of Astronomy*, Prof. Young's *General Astronomy*, and the articles by Prof. Newcomb on "Astronomy" and Prof. Hale on "Spectroscopy" in the *Encyclopædia Britannica*.

I am indebted to the Astronomer Royal Sir William Christie, Prof. Barnard, Prof. Ritchey and other astronomers for permission to reproduce photographs published by them, and to Mr. W. B. Blaikie for the map taken from his Monthly Star Maps published by the Scottish Provident Association.

I wish to express my thanks to a number of friends for help in various directions. Mr. Heath, first assistant of the Royal Observatory, Edinburgh, copied a number of photographs and supplied me with the drawing on p. 172; Mr. Storey, assistant at the Observatory, and Mr. MacGregor assisted with the diagrams. I am much obliged to Mr. Storey and to Dr. J. Reynolds Green, who read the book in proof, for their valuable criticism and suggestions.

F. W. Dyson.

Royal Observatory, Edinburgh,
March 7, 1910.

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CHAPTER I

ANCIENT ASTRONOMY

ASTRONOMY is the oldest of the sciences. The orientation of the pyramids or of Stonehenge, the mythology of the Greeks and the religious festivals of the Jews are familiar evidences of astronomical knowledge in early civilizations. The constant repetition, day by day, month by month, or year by year, of similar phenomena both invited and aided study of the heavenly bodies. Before the dawn of history men wondered what caused the rising and setting of the Sun and Moon each day, why the Moon went through her phases each month, and why Orion reappeared each year in the sky as surely as the seasons returned. An out-of-door life was favourable to a knowledge of the heavens, and the tribes of Chaldea and Arabia two or three thousand years ago were, perhaps, better acquainted with the appearance of the sky than we are to-day. Modern conditions of life are not favourable to the general cultivation of practical astronomy. Buildings circumscribe the view of the sky, clocks and watches save us the trouble of observing the Sun and stars for time, and artificial illumination makes us independent of moonlight. But the following phe-

nomena of the skies ought not to be merely read of in books, but should be verified by actual observation.

(1) The diurnal movement of the Sun; the different positions of the Sun in the sky in summer and winter.

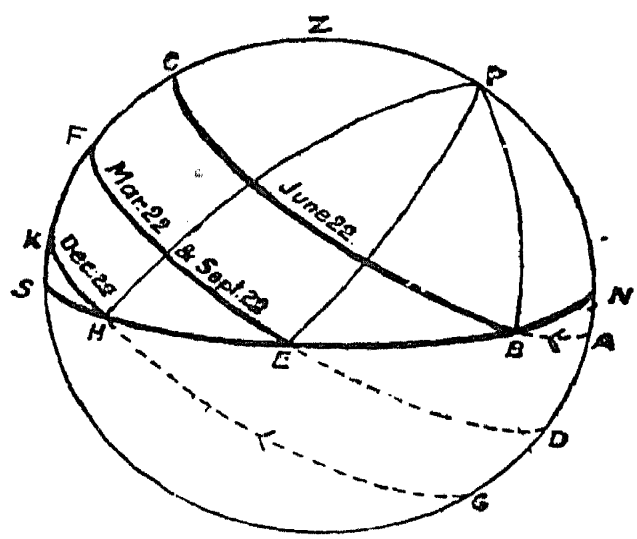
(2) The phases of the Moon; the rapid movement of the Moon among the stars.

(3) The diurnal movement of the stars; the appearance of different constellations at different times of the year.

Observation of the Sun.—In the latitude of London the Sun rises on midsummer day at about 3 h. 45 m. at a point on the horizon considerably north of east. At midday, when due south, it is high in the sky. If we take a stick and point it horizontally and turn it gradually towards the vertical, we shall not be pointing to the Sun till the stick has been turned through rather more than two-thirds of the right-angle between the horizontal and vertical directions. It sets in the evening about 8 h. 19 m. at a point on the horizon considerably north of west. From midsummer to midwinter it rises later and sets earlier each day; the point of the horizon where it rises gradually shifts from north of east to due east, and then to south of east; and the point where it sets shifts in the other direction from north of west to due west, and then to south of west. In midwinter the Sun rises at 8 h. 7 m. and sets at 3 h. 51 m., and at noon, instead of being high up in the sky, it is only 15°, or one-sixth of a right-angle, above the horizon.

From midwinter to midsummer the days lengthen and the Sun at noon is higher each day. Midway between midsummer and midwinter, on March 22 and Sep. 22, the Sun rises due east and sets due west, and day and night are equal in length. This succession of phenomena repeats itself year by year, and is more striking in the latitude of the British Isles than in the more southern countries from which our astronomical knowledge was derived.

Diagram I illustrates the path of the Sun across the sky at different times of the year. The circle NES is the horizon, and NPZS the meridian or circle of the sky cut by a vertical plane in a direction due north and south. The diagram represents the eastern half of the sky—the part above NES being above the horizon and visible, and the part below NES below the horizon and invisible.



Diag. I.

On midsummer day the Sun travels from A to C between midnight and midday, crossing the horizon at B (*i.e.* rising) at 3 h. 45 m. All points of the circle ABC are $66\frac{1}{2}°$ from P, *i. e.* if we divide the arc of the sphere from the pole P to the opposite one into 180 parts, all points of the circle ABC are $66\frac{1}{2}$ parts from P. But on Septem-

ber 22 the Sun is 90° from P. At midnight on that day it is at D, rises at E (due east) at 6 h. 0 m., and is at its highest point F (due south) at 12 h. 0 m. When we come to December 22 the Sun is 113½° from P. At midnight it is at G, does not reach H, *i. e.* does not rise till 8 h. 7 m., and is at K (due south) at 12 o'clock.

Solar Day.—It is not quite correct to say that the Sun is due south exactly at 12 o'clock, but this is sufficiently true for the explanation given in the last paragraph. The interval of time between the moment when the Sun is due south one day to the moment when it is due south the next is called the solar day, and is the natural unit of time. The length of the solar day is not quite constant, but varies to the extent of one minute at different times of the year. Its average length throughout the year is the mean solar day, and is exactly the 24 hours of our clocks and watches.

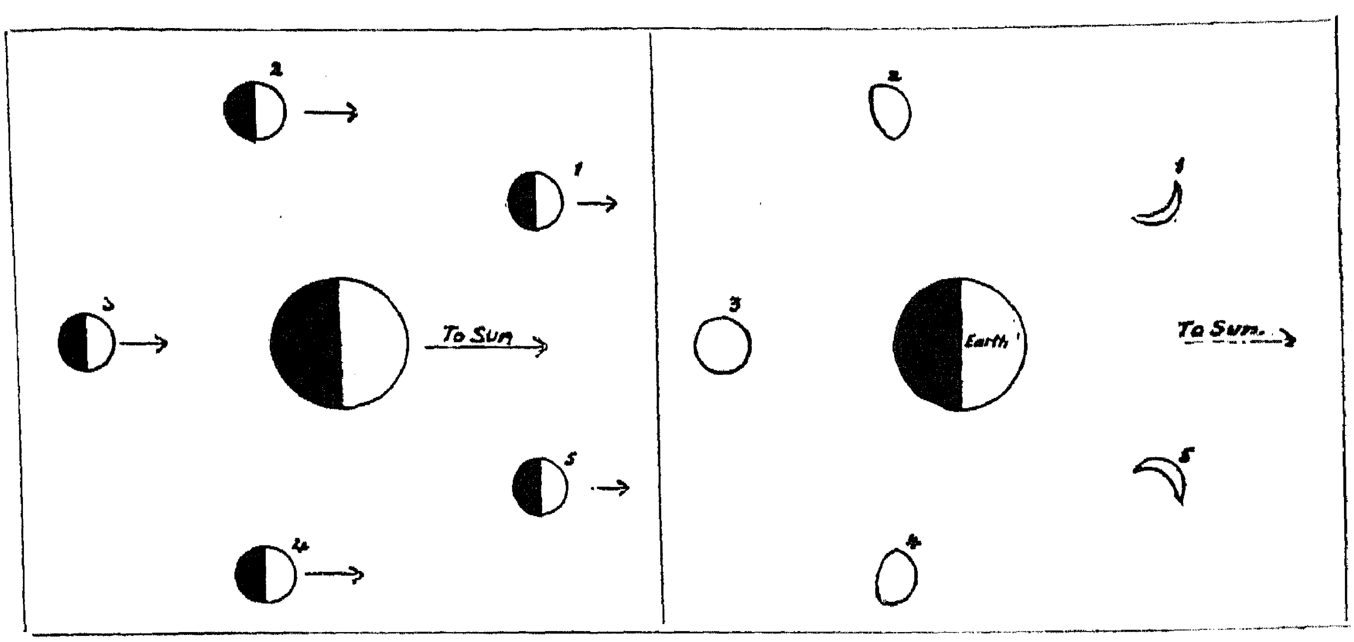
Year.—The exact time the Sun takes to go through the cycle of changes described above is the year. The length of the year can therefore be found approximately by counting the number of days from a particular day in any year to the day in the following year when the Sun is the same height in the sky at noon. When the Sun's height at noon, or, in technical language, its *altitude*, is measured accurately, it is found that after 365 days have elapsed from March 22 the Sun is not quite so high, but after 366 days is higher. Thus the year does not consist of an exact number of days.

The Greek astronomer, Hipparchus, made accurate observations which showed that the year was rather less than $365\frac{1}{4}$ days—a year of $365\frac{1}{4}$ days giving, according to his calculations, an error of only one day in 300 years.

Calendar.—It is hardly necessary to refer to the difficulties different nations experienced with their chronology till a civil year was devised, whose average length was equal to that of the actual solar or tropical year. Our calendar is derived from the one introduced by Julius Cæsar with the advice and assistance of Sosigenes. Every fourth year on this system is a leap year, and consists of 366 days. The error, according to this reckoning, is more than was supposed by Hipparchus, and is very approximately 3 days in 400 years. In course of time this small error accumulated, till in 1582, the equinoxes, midsummer day, etc., all fell on dates 10 days different from those on which they had fallen in A.D. 325, the year of the Council of Nice. In the reformation of the calendar, which was then introduced by Pope Gregory XIII, it was ordained that the centurial years should not be counted as leap years unless the number of centuries is divisible by 4 without remainder. Thus 1700, 1800, 1900 are not leap years, but 2000 is a leap year. With this correction the average length of the civil year only differs from the solar year by one day in about 3300 years.

Observation of the Moon.—Each month the Moon changes from new to full and from full to new.

These changes in the Moon's appearance are called its phases, and observation shows that as the phase of the Moon changes the angle between the directions of the Sun and Moon changes also. The new Moon is always seen in the west near the setting Sun; when half illuminated its direction makes a right-angle with that of the Sun; and when full, its direction is diametrically opposite to that of the Sun. The correct interpretation of the Moon's phases was given by Aristotle (384–322 B.C.), viz. that it is a spherical body, illuminated by the very distant Sun. One half of the sphere is bright and the other dark. The appearance of the Moon from the Earth depends on whether the Earth is in a position from which much or little of the illuminated part is visible.



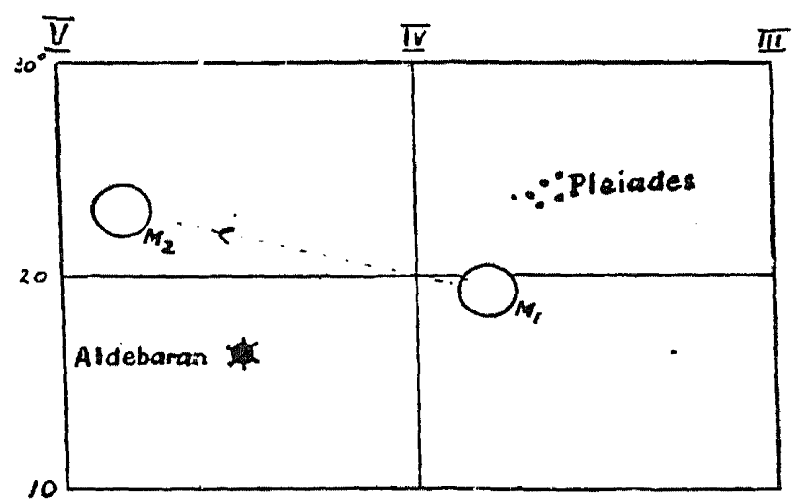
Diag. II.

In the right half of Diagram II the appearance of the Moon is shown: (1) a few days after it is new; (2) shortly after first quarter; (3) full; (4) shortly be-

fore third quarter; (5) a few days before it is new. In the left half the illuminated and unilluminated parts of the Moon are shown at corresponding times.

Another observation which the reader should make consists in noting the position of the Moon with reference to the stars on two consecutive nights. In this way its rapid movement across the sky will be duly appreciated. The distance moved in 24 hours will be found to be very considerable, approximately 12°, or $\frac{1}{30}$th part of the whole circumference of the sky. Diagram III illustrates this: if the Moon is at M_1 one night, it will be at M_2 at the same time on the following night.

Further observations of the Moon will show that it is always to be found in a certain narrow belt of stars. This belt is called the *zodiac*, and its central line is the *ecliptic*. The ecliptic is an imaginary circle which divides the whole sky into two equal portions, and is exactly like the line formed on a globe by its intersection with a plane passing through the centre.



Diag. III.

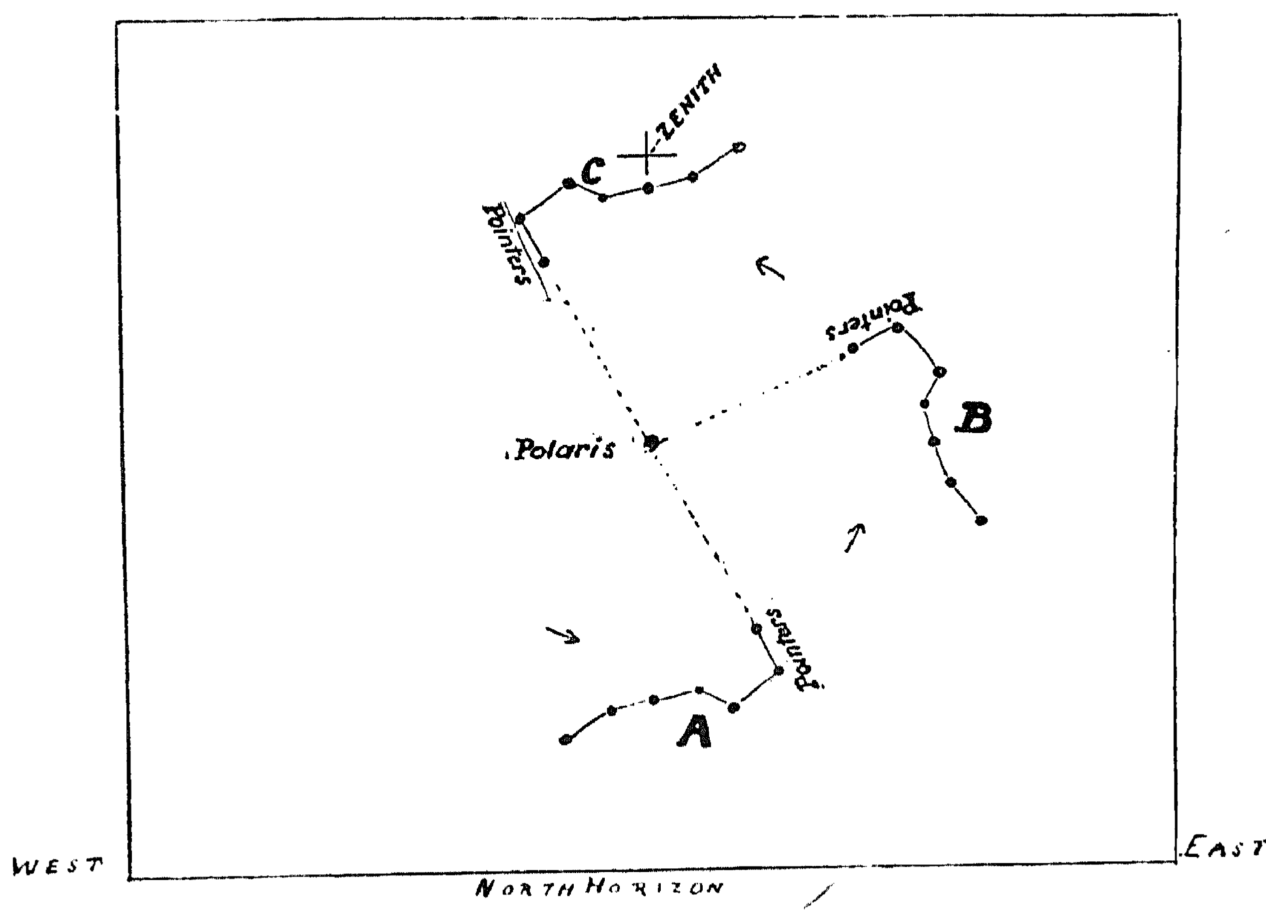
Month.—It is well worth while to verify for oneself that when the Moon is new, it is in the same part of the sky as the Sun, and that it travels round the sky and reaches the Sun again in one month. The length

of the month is approximately $29\frac{1}{2}$ days, but varies a little from month to month. The times of new and full Moon were carefully investigated by the ancient astronomers for purposes of chronology.

Meton's Cycle.—As a lunar month consists of approximately $29\frac{1}{2}$ days, twelve months will contain approximately 354 days, and as this is $11\frac{1}{4}$ days short of the year, considerable difficulty was experienced in harmonizing a system of chronology depending on the Moon with one depending on the Sun. Meton, who lived between 400 and 500 B.C., discovered (if, indeed, the discovery is not older) that in 6940 days there are almost exactly 19 years, and also 235 lunar months. Consequently, if the dates of new and full Moon are known for 19 years, the same dates will serve for the next 19 years, and so on. A little complication arises in practice from the way leap years happen to fall; but this cycle discovered by Meton is still the basis by which Christian countries fix the festival of Easter. As showing the accuracy attained by Meton in the measure of the length of a month, it may be noted that modern observations show that 235 months is about $7\frac{1}{2}$ hours less than 6940 days, or that Meton's rule makes the month only two minutes too short.

Observation of the Stars.—We will now make a preliminary observation of the stars. In the northern hemisphere the Great Bear is one of the most striking constellations. Its appearance is well described by its American name, the Dipper. When it is once recognized it can always be found without any diffi-

culty. Its position in the sky is different at different times of the night and at different times of the year. But it always preserves the same form; the stars do not change their relative positions, but the constellation moves as a whole.

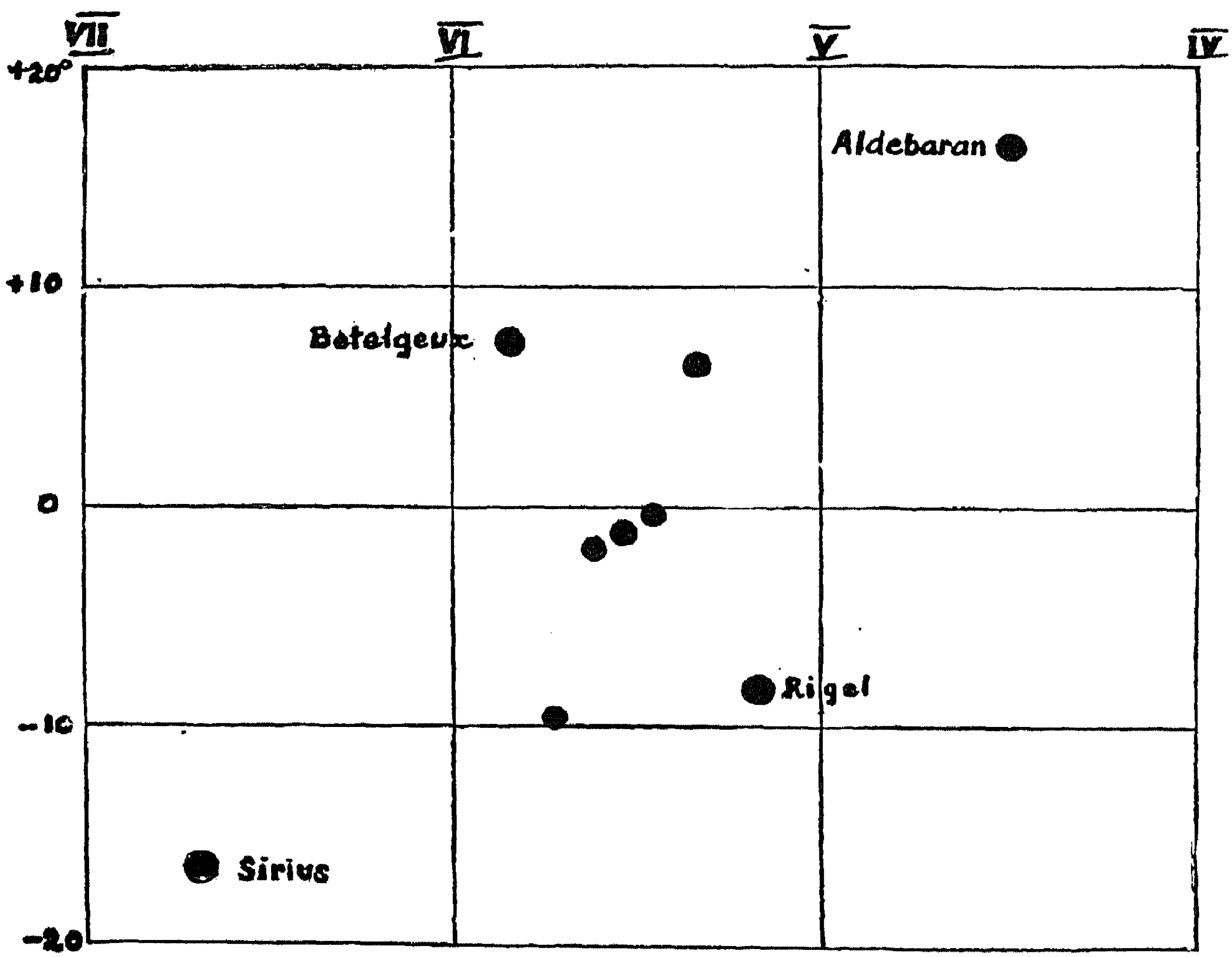


Diag. IV.

The character of this movement is easily seen. If a line be drawn, as in Diagram IV, and produced, it passes nearly through another star. This star, called the Pole Star, is always to be found by looking due north and (in the latitude of Great Britain) at an altitude of about 53°, or somewhat above the point midway between the zenith and the northern horizon. If the Great Bear be watched at intervals for a few

hours it will be seen to be turning about the Pole Star. In the diagram its position, marked A, B, C, is shown at 6 p.m., midnight, and 6 a.m. on January 1. Not only the Great Bear, but all the stars are seen to partake of this motion at the same rate. The time they take to make a complete revolution is evidently not very far from a day, for on consecutive days at the same hour they are in nearly the same positions.

If we take a constellation further from the North



Diag. V.

Pole, like Orion, we find that, unlike the Great Bear, it cannot be seen at all times of the year. On January

1 Orion is a little to the west of south at midnight; on April 1 it is nearly setting in the west at midnight; on July 1 it is not seen, and October 1 it is rising in the east at midnight. But its appearance shows no change, and its position is always midway between Aldebaran and Sirius. At whatever part of the year it is observed it describes the same journey in the sky, rising at the same point of the horizon, reaching the same altitude when due south and setting at the same point of the horizon. The stars of this constellation, like those of the Great Bear, keep at constant distances from the pole.

The movement of the stars in the sky is exactly what we should see if we were at the centre of a

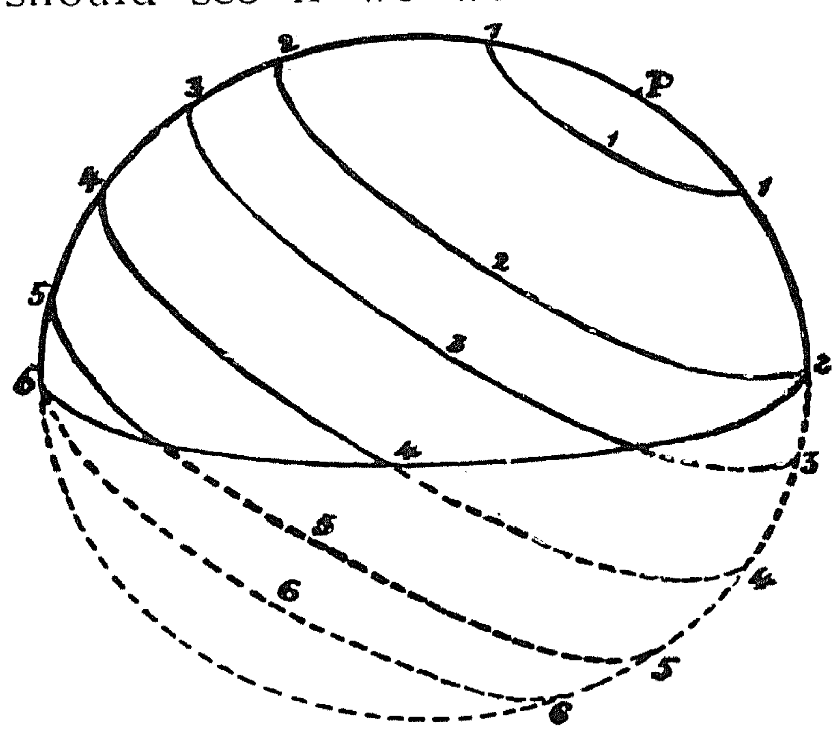


Diagram of Circles (VI).

great globe on which they were fixed, and the globe turned about an axis pointing to the pole. Thus, in Diagram VI, which represents the eastern half of a

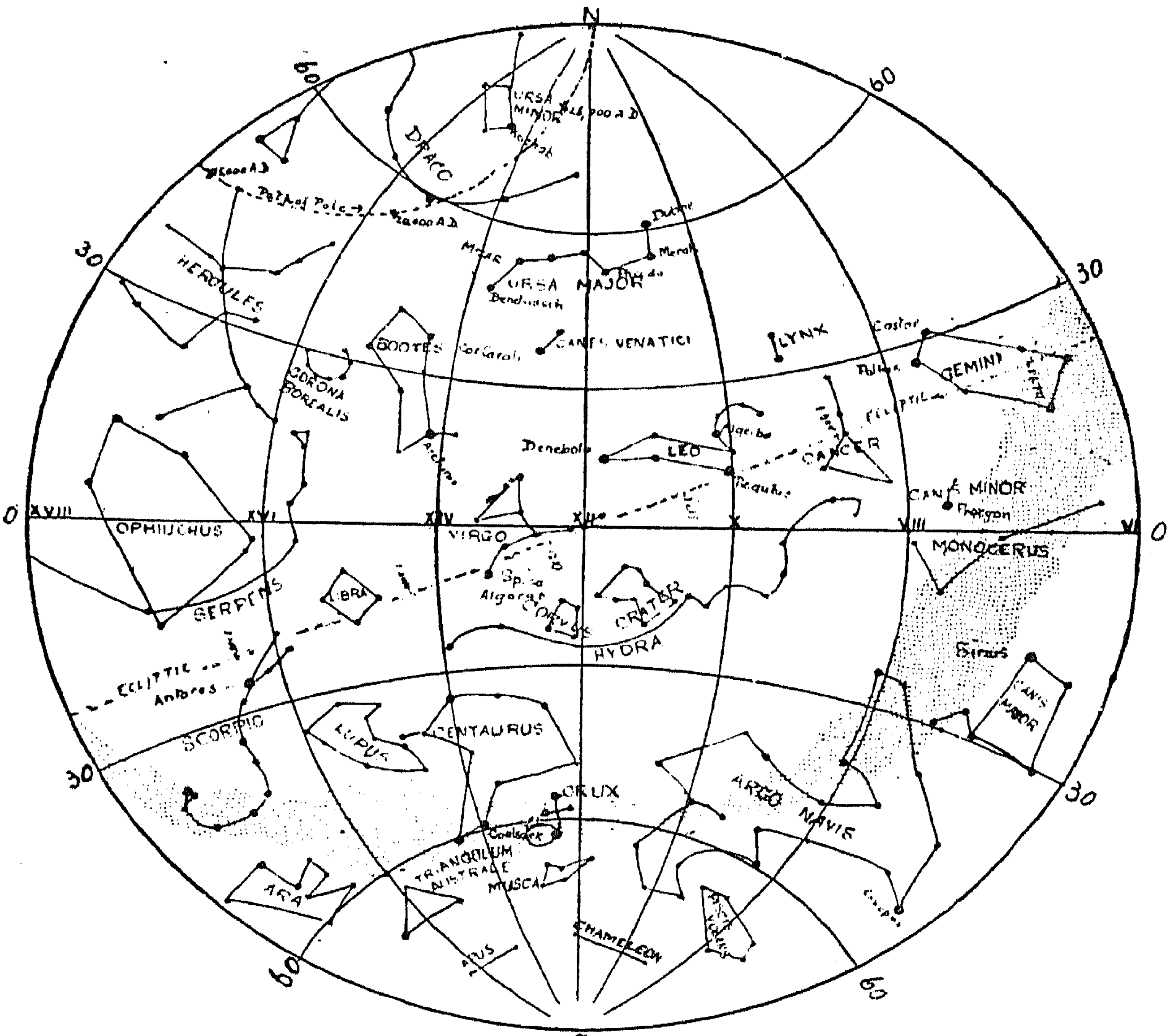
globe, 111 is the path of a star which never sets; 222 of a star which is just at such a distance from the pole that it rises at the north point of the horizon; 333 is the path of a star still farther from the pole, which rises to the north of east and is above the horizon for the greater part of its path but below it for a shorter (dotted) part; 444 is the path of a star which is 90° from the pole, and for half of its path it is above the horizon, for the other half below it and invisible; 555 shows the path of a star more than 90° from the pole, the part of its path during which it is above the horizon is less than half, and such a star rises at a point south of east; 666 is the limiting path of a star which never rises in the latitude for which the diagram is drawn.

This representation of the stars as fixed points on a turning sphere agrees with the facts that the stars do not change their relative positions, and that all describe parallel circles in the sky in the same time. This time is approximately 4 minutes less than 24 hours. Thus each star is at the same point of its daily path 4 minutes earlier than it was on the preceding day. In a month this makes the very perceptible difference of two hours, and those stars which rise and set, rise and set two hours earlier each month. Thus the stars which are seen due south at midnight at one time of year are due south at midday after six months. They are not seen, owing to the glare of the sunlight, but that is the only reason, and with a

telescope fairly bright stars may be seen in the middle of the day.

The stars, then, do not change their positions in the sky relatively to one another, but they all move together like so many points pricked on a vast sphere which turns uniformly about an axis pointing to the pole. This very ancient discovery is important because it states these everyday phenomena of the fixed stars succinctly and accurately. It also furnishes us with a new point of view with regard to the movements of the other heavenly bodies, the Sun, Moon and planets. Instead of considering their movement across the face of the sky, we may consider their movements with reference to the stars. That the five planets, Mercury, Venus, Mars, Jupiter and Saturn do not remain in the same position relatively to the fixed stars, but wander among them, is very readily seen. Their motion is not nearly so quick as that of the Moon, illustrated in Diagram III, but is evident for some of them when their positions are compared after an interval of a few days, and for others after a few weeks. The Sun, however, presents a difficulty. Its light obscures the stars, and prevents a direct determination of its position on the celestial sphere. By carefully observing the position of the Sun just before it sets relatively to Venus or the Moon, and afterwards when the night was dark enough for the stars to be seen, observing the position of Venus or the Moon relatively to the stars, early astronomers were able to mark the position

of the Sun day by day on the celestial globe. This is a very easy task in a modern observatory, thanks to the instruments we now possess for measuring angles, and clocks for accurately measuring time. But with



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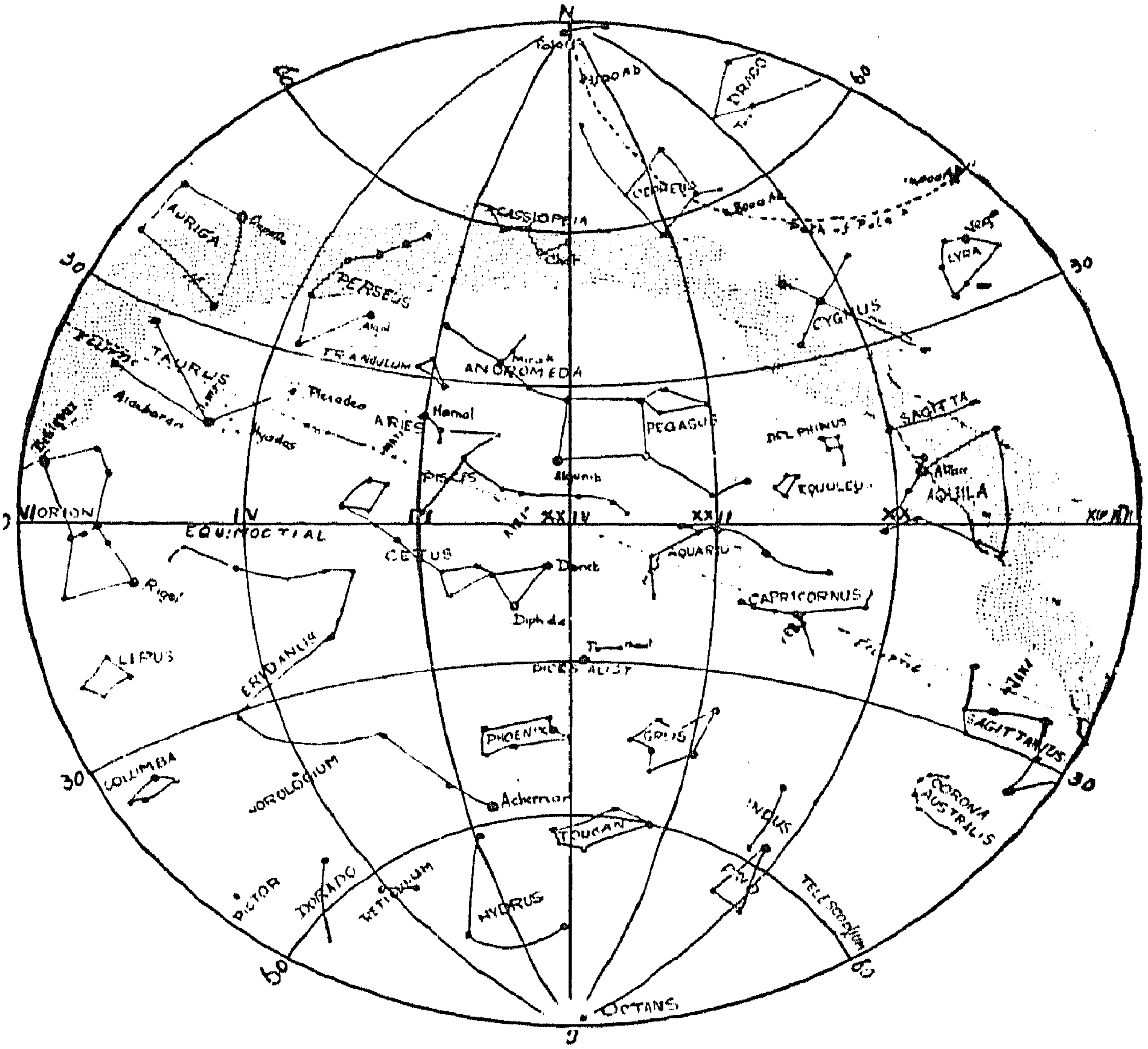
Diag. VII.

the simple apparatus possessed by the Chaldeans, Egyptians and Greeks it was far from being an easy task.

In the accompanying map, which represents two

halves of a celestial globe on which all the brightest stars are marked, the position of the Sun is marked for the first day of each month. It will be seen that these positions all lie on the dotted line called the



Diag. VII.

ecliptic. This line is an imaginary circle dividing the sphere into two equal parts. It is a fixed line among the stars and goes through the constellations enumerated in the doggerel lines—

The Ram, the Bull, the Heavenly Twins,
And next the Crab, the Lion shines,
  The Virgin and the Scales ;
The Scorpion, Archer, and He-Goat,
The Man that bears the watering-pot,
  And Fish with glittering tails.

It is important to notice that the Sun makes this same journey among the stars each year and that its journey is intimately associated with the changes of its position in the sky referred to on pp. 2, 3, and illustrated in Diagram I. For the circle of the ecliptic on the globe is in some parts nearer to the north pole than in others. It cuts the *equinoctial* or circle in the sky midway between the poles in two points which are 90° away from the poles, and half-way between them is, as shown in the map, $23\frac{1}{2}°$ nearer to or farther from the poles. On March 22 the Sun's position in the ecliptic is at one of the points where the equinoctial is cut. It is then 90° from the poles, and its path in the sky on that day is the circle DEF of Diagram I. The days and nights are equal, and the Sun rises due east and sets due west. The Sun moves along the ecliptic through Pisces, Aries and Taurus, and on June 22 it has reached a point $66\frac{1}{2}°$ distant from the north pole. During this period the days have lengthened and the nights shortened in the northern hemisphere.

The converse process goes on in the next three months while the Sun passes through Gemini, Cancer and Leo, till on September 22 the days and nights are again equal. The Sun continues to move farther from

the north for the next three months till December 22, when the shortest day in the northern and longest in the southern hemisphere occurs. It then moves northward, and on March 22 completes its circle.

This annual movement of the Sun accounts for the changing of the constellations visible at night at different times of the year. For example, in June at midday Orion is in the southern sky below the Sun, and with a telescope the brighter stars may sometimes be seen, but it is in December, when the Sun is at the opposite part of the sky, that Orion is seen towards the south at midnight.

The discovery of the movement of the Sun among the stars is the first great landmark in the history of astronomical science. The date of the discovery is very uncertain, and has to be inferred from slender evidence like the names of the constellations through which the Sun passes. It is probably between 2000 and 3000 B.C.

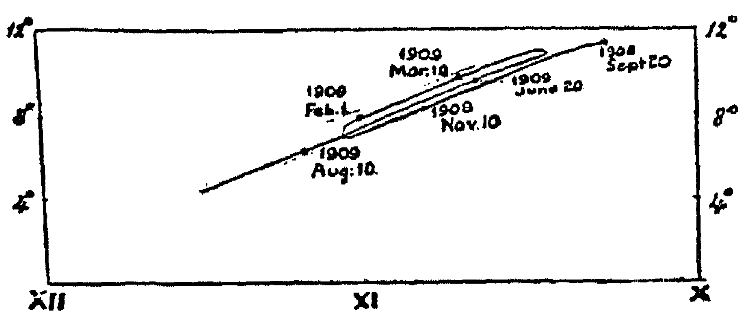
Eclipses of the Sun and Moon.—Eclipses of the Sun and Moon, especially of the Sun, are very striking phenomena. Excluding the Chinese accounts, the earliest eclipse of which we have any record is referred to on a Babylonian tablet and has been identified with one which occurred in 1062 B.C. Some verses in the Book of Amos, *e.g.* chapter viii., ver. 9, "to darken the earth while it is yet day," may be taken as an indication that the writer had seen the total eclipse of the Sun which passed across Samaria on June 19, 763 B.C.

From the fact that Thales is said to have predicted an eclipse which occurred in 584 B.C., it is clear that considerable knowledge of these phenomena was possessed at that time in Ionia. But to the Babylonians belongs the honour of having discovered a law in these apparently very irregular occurrences. It was doubtless perceived soon after records were kept that eclipses of the Sun occurred at the time of new Moon, and those of the Moon at the time of full Moon. The correct explanation was given, viz. the interposition of the Moon between the Earth and Sun in the case of a solar eclipse; and the interposition of the Earth between the Sun and Moon in the case of a lunar eclipse. But as the path of the Moon among the stars does not coincide with that of the Sun, but is inclined to it at a small angle, the three bodies are not sufficiently in a straight line for eclipses to occur at every new and full Moon. The path of the Moon in the sky is a circle inclined at about 5 degrees to the ecliptic, the path of the Sun (see p. 23). The two points of intersection of these circles are called the nodes of the Moon's orbit. If the Moon is sufficiently near a node when it is new or full an eclipse of the Sun or Moon respectively will occur. From our present knowledge of the movements of the Moon and of its nodes—which move round the ecliptic in 18 years and 7 months—it can be shown that after 223 months the relative positions of the Sun, Moon, and the nodes of the Moon's orbit will be nearly the same. Thus after this period

eclipses will recur. This very curious cycle, called the Saros, was discovered by the Babylonian astronomers from their observations of eclipses of the Moon. The period is 223 months or 6585·3 days, or approximately 18 years and 11 days. If, then, the eclipses are recorded which occur in one period of this duration, those in the next period may be predicted, and so on. As the relationship between the numbers is not quite exact, an eclipse may in some cases occur which is not predicted by the cycle, and in some cases an eclipse predicted in this way may not occur, but the extreme cases where the rule fails from one cycle to the next are very few. The date of the discovery of the Saros cannot be fixed with certainty, but must have been some centuries before the Christian era.

The Planets.—Besides the Sun and Moon there are five other celestial bodies visible to the naked eye which move among the stars. Of these Mercury is only occasionally seen in Great Britain. Venus is best known as a brilliant evening star which is sometimes visible in the west about the time of sunset. At other times it is a morning star and rises before the Sun. The identity of the evening and morning star is said to have been discovered by Pythagoras. Venus is always seen in a direction not far from that of the Sun, the largest angle between them being 47°. The planet passes from side to side of the Sun as the Sun pursues its circuit of the sky, and when on one side is seen as the morning star and when on the other as the evening

star. Next to Venus, Jupiter is the most brilliant of the planets. If its position among the stars is plotted down each day on a celestial globe or on a map of the stars, it will be seen to be sometimes moving round the sky in the direction of the Sun's annual motion, but sometimes to be moving in the opposite direction. Its total movement in a sufficiently long interval is in the same sense as the Sun's motion, but the irregularities of its movement will be seen from Diagram VIII, giving its movement from 1908, Sept. 20, to 1909, July 10. Mars and Saturn exhibit a similar irregular movement among the stars. The most important difference between the movements of these three planets is that Mars takes 2 years, Jupiter 12 years and Saturn 29½ years to complete the circuit of the sky.

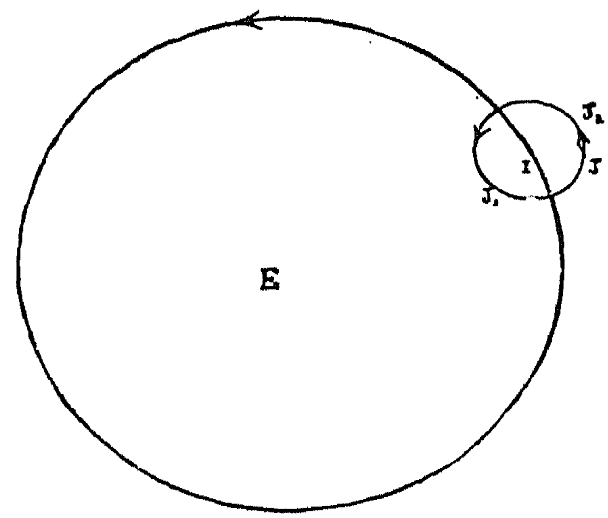


Diag. VIII.

The Greek astronomers succeeded in expressing the observed movements of the planets, as well as of the Sun and Moon, by mathematical formulæ, so that their position could be calculated and predicted. This was an immense step in the progress of astronomy. A formula, however empirical it may be, which correctly represents the facts, simplifies their statement and brings them into orderly arrangement and small compass. As an example we may take the representa-

tion of the movement of Jupiter as given by the Greek geometricians.

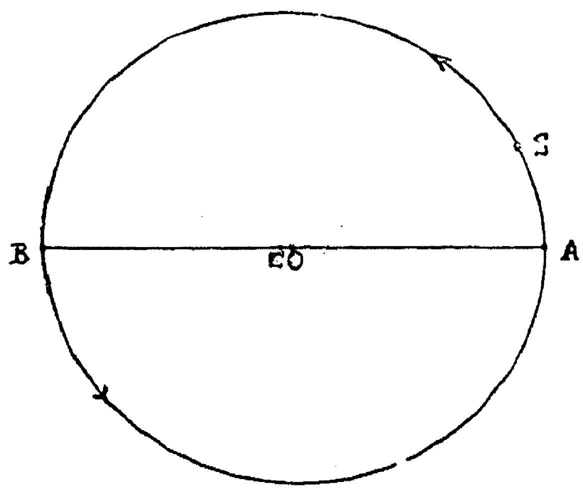
Let the point I in Diagram IX make the circuit of the sky in 12 years. Represent this by the movement of I round the circumference of the circle whose centre is E. Meanwhile let the point J move round a circle of $\frac{1}{5}$ the radius of EI in the course of one year. As seen from E, J when at J_1 will be moving in a retrograde direction, when at J_2 in a forward one. This epicyclic movement of I as seen from E presents the main features of the movement of Jupiter among the stars, namely, its alternate progression and retrogression. Further, by taking the radii of the circles and the periods in which they are described in suitable proportions, the movement of J in the diagram as seen from E agrees in amount with the observed motion of Jupiter in the sky.



Diag. IX.

Hipparchus.— Hipparchus, one of the greatest of all astronomers, lived at Rhodes, and made observations between 146 and 126 B.C. He invented trigonometry, and by its aid made geometrical representations of the motions of the heavenly bodies by means of epicycles, eccentrics, etc., in close numerical agreement with the

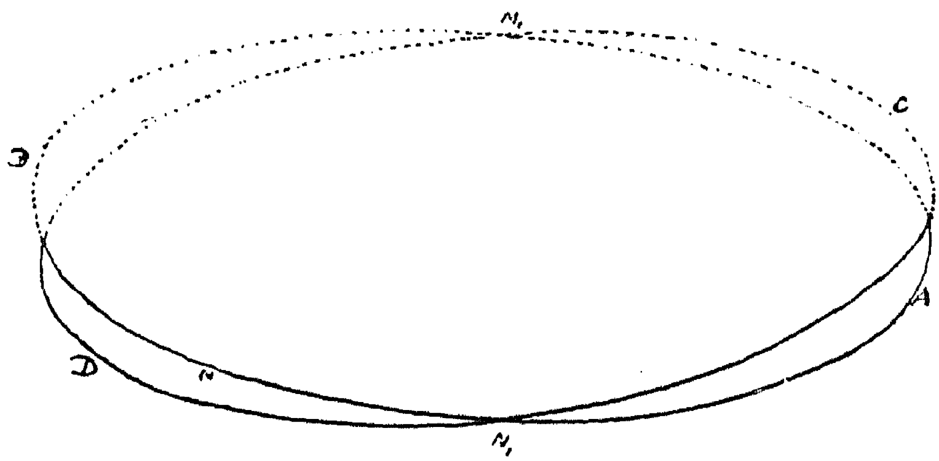
best and most detailed observations which were then possible. For example, it was known that the Sun moved across the sky more rapidly in winter than in summer. Hipparchus showed that the movement would be accurately represented if the Sun moved uniformly round the circle whose centre is O (Diagram X), but the earth from which it is seen had the slightly eccentric position E. He fixed the position of E as being $\frac{1}{20}$th part of the radius distant from O, and in such a direction that the Sun was at A on June 1.



Diag. X.

Hipparchus made a great step in unravelling the motion of the Moon, which, when observed in detail and with accuracy, is extremely complicated. As in the case of the Sun he found that its varying rate of motion could be represented by supposing the Earth to be placed eccentrically in a circle whose circumference was uniformly described by the Moon. He discovered that to represent the motion accurately the line corresponding to EA of the last diagram revolves in a time which he fixed at 9 years. This is known as the movement of the apse. He also determined the inclination of the Moon's orbit to that of the ecliptic to be 5°, and showed that the points where the circle which the Moon traced on the celestial sphere cut the

ecliptic are not fixed but move round in a period of 19 years. Thus in Diagram XI, if N_1AM_1B is the ecliptic, and N_1CM_1D the Moon's orbit; the angles at N_1 and M_1 were found to be 5°; and the points N_1,



Diag. XI.

M_1 carrying the circle N_1CM_1D with them moved round N_1AM_1B in 19 years.

Perhaps the most famous of the discoveries of Hipparchus is that of the *precession of the equinoxes*. In the year 134 B.C. the appearance of a new star in the constellation Scorpio led Hipparchus to make a catalogue of 1080 stars for comparison with catalogues made at other dates. He determined the position of the stars with all possible precision. When he compared this catalogue with earlier ones he found that the stars had shifted their positions with reference to the equinoxes or points in the sky where the ecliptic cuts the equinoctial. As the stars all showed the same shift, the change in their positions was attributed by him to a movement of the equinoxes in an opposite direction.

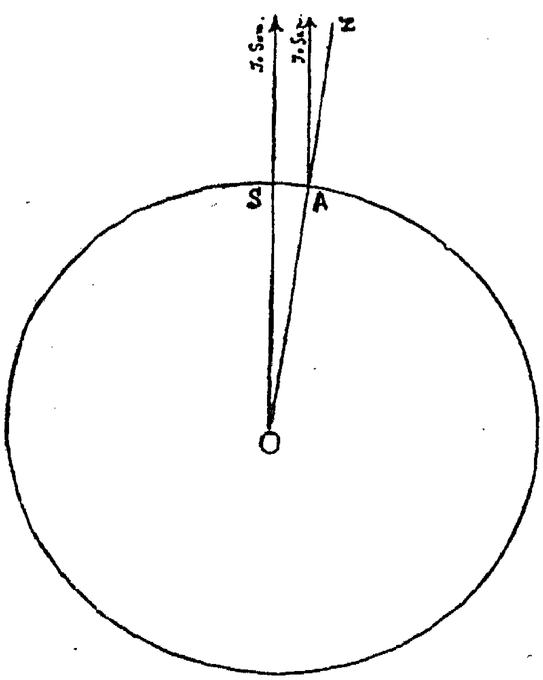
The meaning of this discovery will be understood more clearly by reference to the map on pp. 14, 15. The ecliptic or path of the Sun among the stars does not change; its course is through the constellations of Aries, Taurus, etc. But in the map it will be seen that the Sun is midway between Pisces and Aquarius at the time when it crosses the equinoctial, *i.e.* at the time in spring when the Sun is just 90° from the pole and the days and nights are equal. In the time of Hipparchus the equinoctial was in a different position and cut the ecliptic at a point in the constellation Pisces, 28° from its present position. The equinoxes move round the ecliptic in 26,000 years, a movement discovered by Hipparchus by the differences between his catalogue and one constructed 150 years previously. Now the pole of the sky bears the same relation to the equinoctial as the pole of the Earth does to the Equator, being 90° away from every part of it. As the equinoctial moves the pole necessarily moves too, and thus precession states that the point of the sky about which the stars turn slowly changes its position, describing among the stars in 26,000 years a small circle whose radius is 23½°. At present the pole is near the star Polaris. Its positions 6500 years ago and 13,000 years ago are shown on the map.

The effect of the precession of the equinoxes is to change the time of year at which the constellations are visible. Orion is at present a winter constellation. We see it due south at midnight in December. 6000

years ago it was due south at midnight in the autumn. In 6000 years more it will be due south at midnight in the spring. These changes brought about by precession in the positions of the stars in relation to the seasonal changes of the Sun can be in some instances used for chronological purposes. For example, Hesiod gives information about the times of rising and setting of Sirius at certain times of the year—the year being defined by the seasons—which can be used to verify the approximate date at which he wrote. The approximate dates of some of the pyramids and some temples have been determined by more or less conjectural relationships between the position of the Sun and some bright star at the time of their erection, the rising of the star having been used as a warning of the approach of sunrise at the equinox or at midsummer's day.

The Distance of the Sun, Moon, and Planets.—That the Earth is a sphere was believed by Plato and Aristotle. Their reasons were the same as those given in modern books on geography, except the reason which might be expected to convince even the least reflective, namely, that people have been round it and nearly all over it. *Eratosthenes*, the librarian at Alexandria, who lived from 276 to 196 B.C., first determined its size. He observed that at the summer solstice the Sun was vertically overhead at Syene in lower Egypt, but at Alexandria made an angle with the vertical of $7\frac{1}{5}°$ or $\frac{1}{50}$th part of the circumference of a circle.

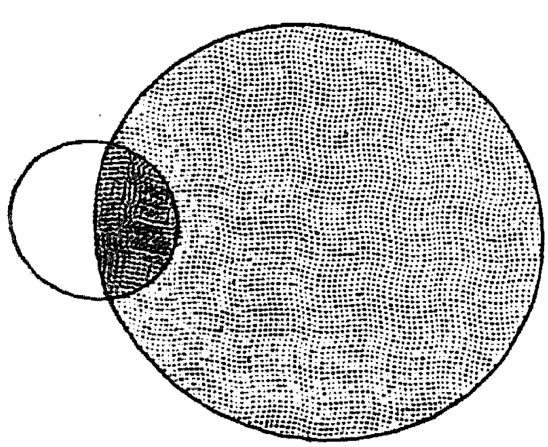
Taking the Sun to be at a distance so much greater than the distance AS, Diagram XII, that the lines from A and S to the Sun are parallel, the angle AOS between the verticals at the two places is $7\frac{1}{5}°$. Thus AS : Circumference of Earth = $7\frac{1}{5}° : 360° = 1 : 50$.



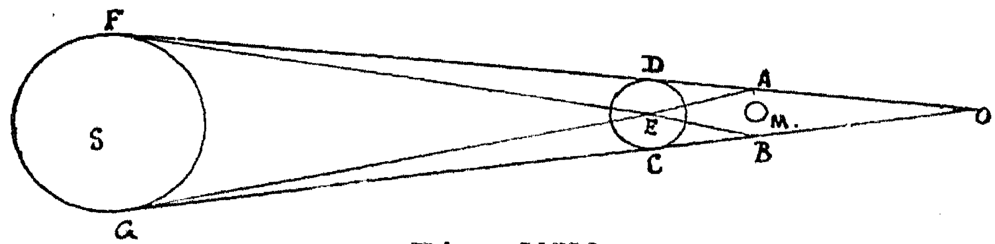
Diag. XII.

The distance between Syene and Alexandria was measured and found to be 5000 stadia, and therefore the circumference of the earth was 250,000 stadia. The value of a stadium is not known exactly, and the accuracy of the result cannot be stated, but the method is sound and the result not far from the truth.

Knowing the size of the Earth Hipparchus was able to measure the distance of the Moon. When the Moon is partially eclipsed the edge of the shadow of the Earth is seen as part of a circle on the Moon, as in Diagram XIII. The size of this circular shadow is compared with the size of the Moon. The apparent diameter of the Moon is $\frac{1}{2}°$ or $30'$; thus it is found that the shadow of the Earth at the


Diag. XIII.

distance of the Moon subtends an angle of 80′. Diagram XIV, in which S, E, M are the Sun, Earth and



Diag. XIV.

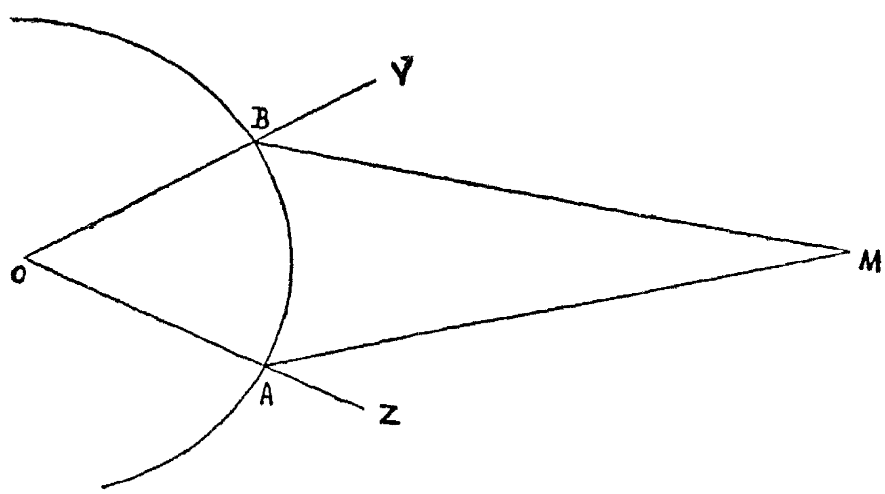
Moon, shows how the shadow is formed. The angle AEB is thus found to be 80′, while the angle FEG under which the Sun is seen is 30′.[1] [In the diagram these angles are necessarily grossly exaggerated.]

With these data, and making the assumption that the Sun's distance is 20 or 30 or any large number of times the Moon's distance, Hipparchus found that the Moon's distance from the Earth was about 59 times the radius of the Earth, and that the result did not vary much with the different hypotheses made as to the Sun's distance provided it was a good many times larger than that of the Moon.

Ptolemy, who lived at Alexandria about A.D. 150, determined the distance of the Moon by a method which is substantially the one now adopted. If at the same moment the position of the Moon be observed from two places A and B at a considerable distance apart on the earth (Diagram XV); and ZAM, YBM,

[1] The angle through which we turn in looking from one direction to a perpendicular one is called a right-angle. If this angle is divided into 90 equal parts, each is called one degree, and written 1°. One-sixtieth part of a degree is called a minute, and written 1′. One-sixtieth part of a minute is called a second, and written 1″.

the angles between the directions of the Moon, and the verticals at the two places be measured; knowing the positions of A and B on the Earth's surface, it is possible to draw the diagram below to scale and thus infer how large OM, the distance of the Moon,



Diag. XV.

is as compared with OA or OB, the radius of the Earth. In actual practice trigonometrical calculations are used, but that is only because drawing to scale cannot be done with sufficient accuracy.

The Moon's distance was thus satisfactorily determined, and Ptolemy tried to use his result in combination with the eclipse method of Hipparchus to obtain the Sun's distance. He found that the Sun was 20 times as far away as the Moon. This is much too small; we know now that the Sun is nearly 400 times as far away as the Moon. The method used by Ptolemy is not susceptible of giving the Sun's distance with accuracy.

The Almagest.—Although Ptolemy made several discoveries of very great importance, the greatest

service he rendered to astronomy consists in his treatise, μεγάλη σύνταξις, or the Almagest, as it was called later by the Arabian astronomers. This work contains the whole body of astronomical knowledge then known, and was for 1400 years an astronomical bible.

The preceding pages give some idea of the immense progress made by the Greeks in astronomy. They had reached correct ideas of the shape and size of the Earth and the distance of the Moon; they knew that the Sun was much farther away than the Moon, and guessed from the rates of movement of the planets round the sky that their distances were of a similar order of magnitude, Jupiter and Saturn being the most distant, while the fixed stars were much farther away. Again, the movements of Sun, Moon and planets had been studied in considerable detail, and geometrical and trigonometrical representations of them had been devised. These representations were sufficiently accurate for the prediction of their positions and of eclipses. In these geometrical representations the Earth was taken as stationary, and movements attributed to the Sun, Moon and planets and the celestial sphere of the stars. It may well be that Hipparchus and Ptolemy regarded as formulæ what their more ignorant successors regarded as dogmas. In any case the skill with which the movements of the heavenly bodies were traced and brought into relationship with geometry made astronomy an exact science of great scope and interest.

CHAPTER II

THE COPERNICAN SYSTEM

Copernicus.—From Ptolemy's Almagest in the middle of the second century, to the *De Revolutionibus* of Copernicus in the middle of the sixteenth century, comparatively little progress was made in astronomy. But the publication of the *De Revolutionibus* in 1543 was the beginning of a new astronomical era. The change from the ancient to the modern conceptions of astronomy is associated with four great names—Copernicus, Galileo, Tycho, and Kepler.

Copernicus stated two propositions—

(1) That the diurnal movement of the stars is apparent only, and results from a rotation of the Earth about its axis in the opposite direction.

(2) That the Earth is one of the planets, and, like them, revolves round the Sun.

These are the commonplaces of modern astronomy; it is, however, both interesting and important to notice the arguments which were adduced in their favour, and those brought against them.

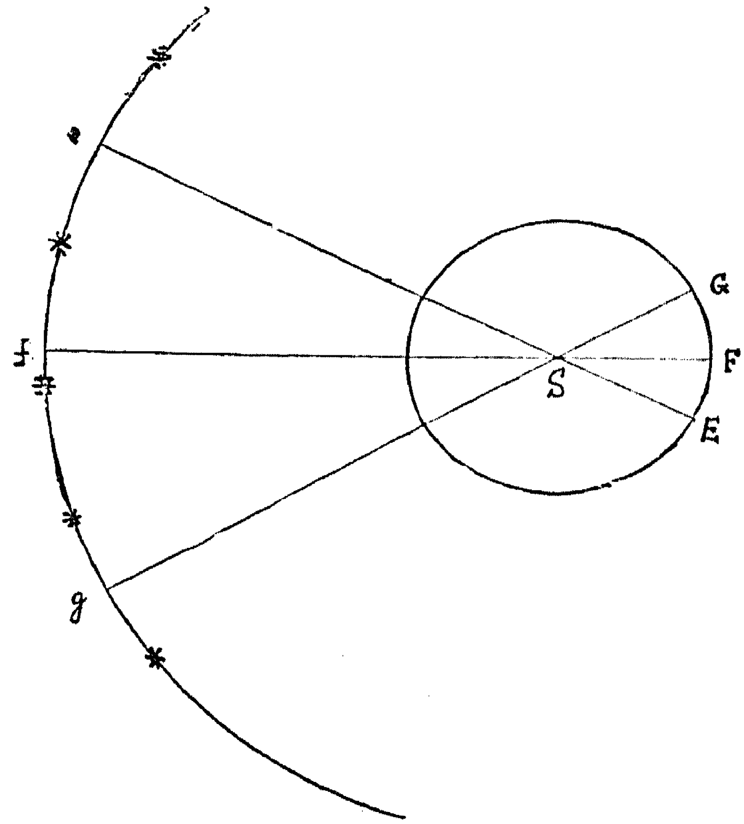
Earth's Diurnal Rotation.—Copernicus showed clearly the relative character of motion. The apparent motion

of objects as seen from the window of a railway carriage is so familiar that it is not necessary to elaborate the proposition that the appearance of motion is equally produced by a movement of the object or the observer. The apparent movement of the stars in parallel circles is identical with the movement which would be produced by a rotation of the Earth about its axis. The objections are, the difficulty of believing in the motion of so large a body as the Earth; that we should be entirely unconscious of this movement; and that movable bodies, specially the air, should not be left behind. Copernicus points out that these objections would apply with far greater force to a rotation of the celestial sphere containing the stars, for this is immeasurably larger than the Earth, and would need to move at an immeasurably greater speed to accomplish a diurnal rotation.

Annual Revolution of Earth round the Sun.—The annual motion of the Sun among the stars is as well explained by an annual revolution of the Earth about the Sun as by that of the Sun about the Earth. In Diagram XVI, when the Earth is at E, the Sun will appear projected against the sky at *e*; when the Earth moves to F, the Sun will appear projected against the sky at *f*, and the appearance of the Sun's annual movement among the stars will be produced.

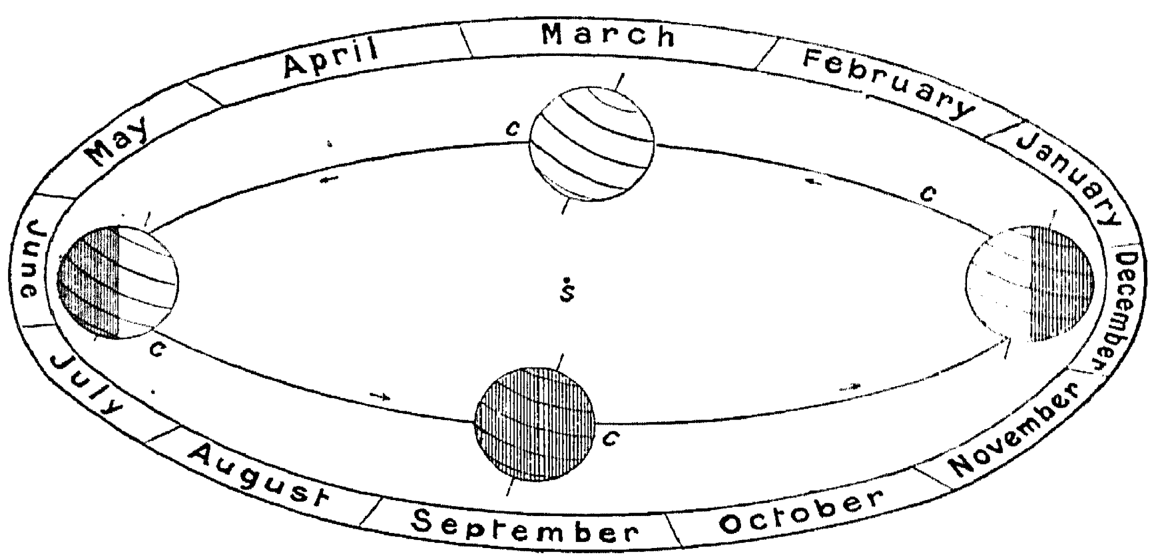
The explanation of the seasons offers no difficulty. The axis round which the Earth makes its daily rotation is fixed in a direction not perpendicular to

the plane in which the Earth revolves round the Sun,



Diag. XVI.

but inclined at $23\frac{1}{2}°$ to this perpendicular. In Diagram XVII the centre of the Earth describes the

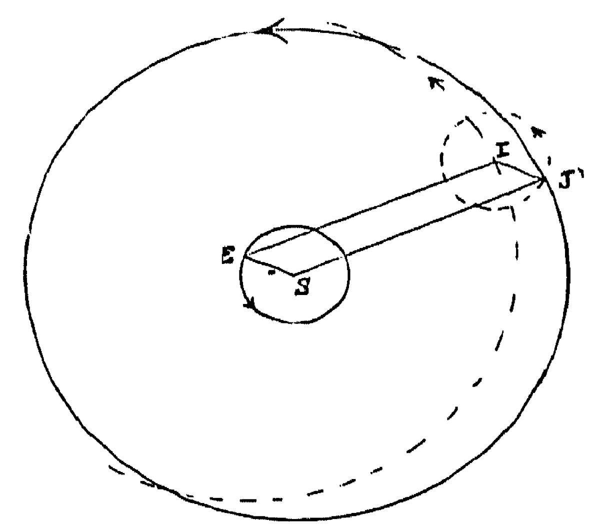


Diag. XVII.

circle CCCC about the Sun in the direction shown by

the arrows. As the axis is not perpendicular to the plane of this circle, in June the northern hemisphere is more directly under the Sun's rays, or the Sun appears higher, being directly overhead at a point north of the equator. Similarly, in December the point on the Earth where the Sun is directly overhead is south of the equator. By running a knitting-needle through a ball of worsted a model can be constructed, with which the movement of the Earth round the Sun can be imitated, and the cause of the Earth's seasonal changes explained.

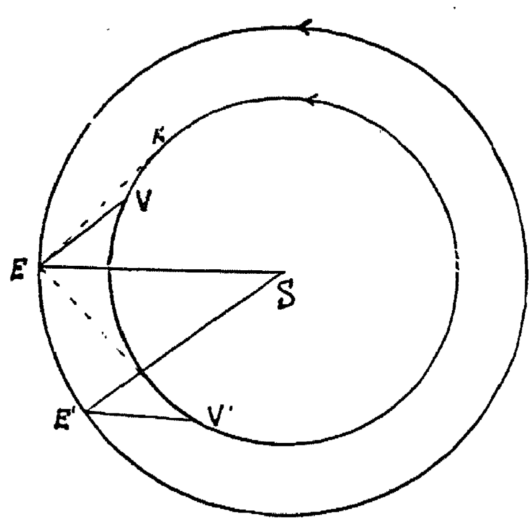
The alternations of forward and retrograde motion of the major planets (see p. 20), which is represented by an epicyclic motion on the Ptolemaic system, is accounted for at once by Copernicus. The movement of Jupiter, for example, is represented in Diagram IX by a movement of I round E (the Earth) in twelve years, while J (Jupiter) moves round I in one year. Diagram XVIII shows how this would be represented on the Copernican system. S is the Sun; E, the Earth, describes a circle round it in one year, J, Jupiter, describes a circle round S in twelve years, the radius being five times SE. If the line EI is drawn parallel to SJ and JI parallel to



Diag. XVIII.

SE, then the points I and J bear the same relation to E as in the Ptolemaic diagram, for EI and IJ are equal in length and in the same directions in the two diagrams. Thus in the Copernican system the apparent motion of Jupiter relatively to the Earth, or as seen from the Earth, is shown to result from a motion of Jupiter round the Sun in a circle, combined with a motion of the Earth—the point from which Jupiter is viewed—in another circle.

The essential features of the movements of the planets Venus and Mercury are readily explained. As they move round the Sun in less than a year, they will necessarily be seen from the Earth first on one side and then on the other side of the Sun. In Diagram XIX, if Venus is at V when the Earth is at E, looking at the Sun from E, Venus would appear on the left hand, while if the Earth reaches E′ when Venus reaches V′, it will be seen on the right hand. Thus Venus will be alternately a morning and evening star, and can never be more than a certain angular distance from the Sun, as it will always be within the angle formed by the two tangents from the Earth to the circle along which Venus moves.



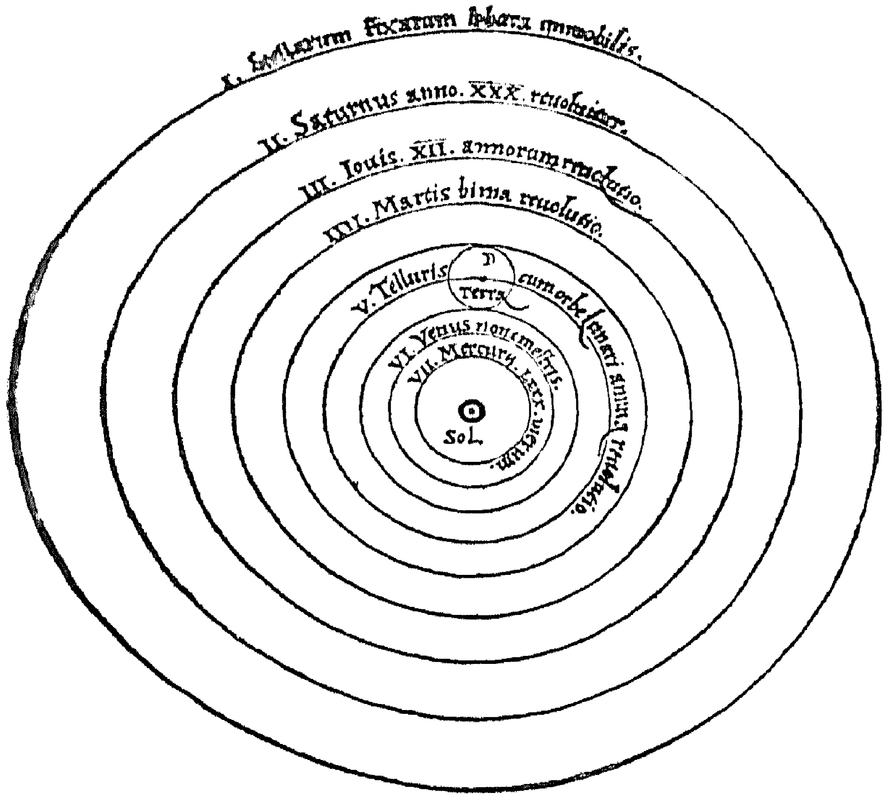
Diag. XIX.

Copernicus further showed how the relative dis-

tances of the planets from the Sun could be obtained. As Mercury never gets so far from the Sun as Venus, it must describe a smaller circle; the knowledge of the greatest angle its direction can make with that of the Sun makes it possible to draw this circle to scale with the one described by the Earth. Similarly with regard to Venus, if EK is drawn so that SEK is the greatest angular distance Venus attains from the Sun, it is only necessary to draw a circle with centre S to give the orbit of Venus. The distances of Mars, Jupiter and Saturn are deducible from the extent of their retrograde motions. Thus Copernicus was able to draw a plan of the solar system, giving the planets in their order of distance from the Sun, and at their proportionate distances. He pointed out that this order agreed with the order which could be inferred from their times of revolution. Thus Mercury, the nearest, goes round the Sun in 88 days, Venus in 223 days, the Earth in a year, etc., and Saturn, the most distant, in 30 years. Diagram XX, taken from the *De Revolutionibus*, gives the order, but not the correct relative distances. It will be noticed that the Moon revolves round the Earth as in the Ptolemaic system, and is carried with the Earth in its orbit round the Sun.

Difficulties of Copernican System.—The Copernican system presented several difficulties. How the Moon could be carried round the Sun with the Earth is a mechanical problem which was not at that time

oluble. Another objection arose from the absence f any appreciable motion of the fixed stars. Their mmense distances are familiar to us now, but at the ime when the Copernican system had to meet riticism their distances might well have been sup-osed to be 10, or 20, or 30 times the distance of



Diag. XX.

Saturn. If the Earth described a circle round the Sun, its positions when on opposite sides are a very great distance apart. It was to be expected that the stars, seen from two points so far apart, would show ome differences of relative position. The only reply which could be given—and it is the correct one—was hat the distances of the fixed stars are so great that he distance between the Earth and Sun is inappre-iable in comparison with them.

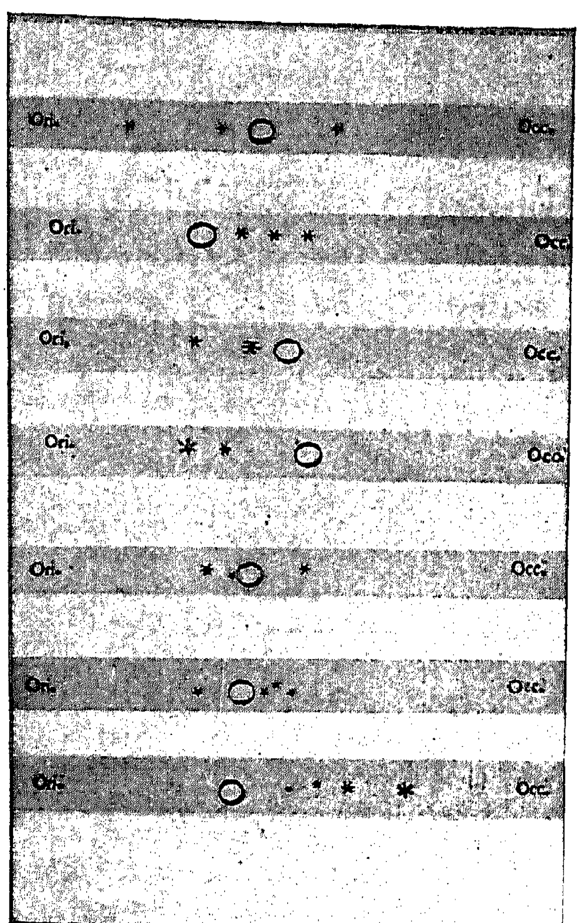
Other objections to the Copernican system were its supposed opposition to the Bible and its disagreement with the orthodox astronomy found in the writings of Ptolemy and Aristotle. Curiously enough the authority of Greek teachers was its greatest obstacle, although freedom of thought is a heritage the world owes so largely to Greek philosophy. It was a hundred years before the Copernican system completely superseded that of Ptolemy.

Galileo.—Galileo supported the Copernican theory by arguments which appealed to a wider audience than the mathematical treatise of Copernicus. In 1609 he learned that a Dutch optician had by a combination of lenses devised an instrument which made distant objects seem near. Galileo realized the optical principles which must underlie such an instrument, and soon made one himself which magnified thirty times. He pointed this to the sky, and found that the number of stars visible was much greater than could be seen with the naked eye.

Seen in his telescope the Moon presented the appearance of a mountainous country with dark shadows cast by the mountains. Near the edge between the bright and dark parts he saw bright spots where the mountain tops were illuminated by the rising or the setting sun, while the valleys were still in darkness. From the lengths of the shadows he calculated the heights of the mountains. Some of the dark parts he erroneously supposed to be water.

Thus the Moon, instead of being a crystal globe, as the old astronomers believed, had mountains and valleys like the Earth.

Pointing his telescope to the planets he found that they were not bright points like the stars, but discs of sensible magnitude like the Sun and Moon. The appearance of Venus was especially striking. It was seen to have phases like the Moon, and the conclusion was irresistible that, like the Moon, it shines by the reflected light of the Sun, and not by its own light. This established a resemblance between Venus and the Moon, and afforded another argument in favour of the Copernican theory.



Diag. XXI.

On January 7, 1610, he saw three small stars in a line with Jupiter (Diagram XXI). By accident he examined Jupiter again on January 8, and found them in a different position. January 9 was cloudy. On January 10 he found two stars both on the east of the planet. On the 11th he found two on the east, but the most easterly one was much the brighter. On the 12th he saw three stars, the third one emerging

from behind the planet during his observations. On the 13th he saw four stars. Galileo perceived that these stars were four satellites revolving round Jupiter just as the Moon revolves round the Earth. He observed them further, and determined their periods of revolution. The analogy between Jupiter and his satellites and the Earth and Moon was another argument for the Copernican theory. As Jupiter's moons revolve around and accompany Jupiter, may not the Earth's Moon accompany the Earth in its revolution about the Sun?

Galileo's telescope revealed to him still another analogy which lent support to the Copernican theory. He discovered spots on the Sun which did not remain stationary, but crossed the disc in fourteen days, and showed changes in appearance which, as he explained, would naturally arise from perspective when the spots were seen at an increasing angle. He concluded that the Sun rotated on an axis. If the Sun, why not the Earth?

In 1632 Galileo published his great work, the *Dialogue on the Two Chief Systems of the World—the Ptolemaic and the Copernican*. The arguments in favour of the Copernican system were put forward with unanswerable force, and the book was received with applause all over Europe. Unfortunately for Galileo, he had made many enemies during a life full of controversy. They procured his trial by the Inquisition, and he was compelled to abjure

his opinions. But, although his book was condemned, the Copernican system was effectively established.

There can be no question of the important part which Galileo's telescope played in the substitution of a system of the world with the Sun as centre (heliocentric) for the Ptolemaic one in which the Earth was the centre (geo-centric). Copernicus put the geometrical arguments with great force in the *De Revolutionibus*, but he had no new facts to bring forward. A heliocentric theory had been previously proposed by the Greek astronomer Aristarchus, and the Babylonian astronomer Seleucus is said to have nearly convinced Hipparchus of its truth. Galileo's telescope transformed the planets from bright points into worlds, and thus added a force to the arguments of Copernicus which made them irresistible.

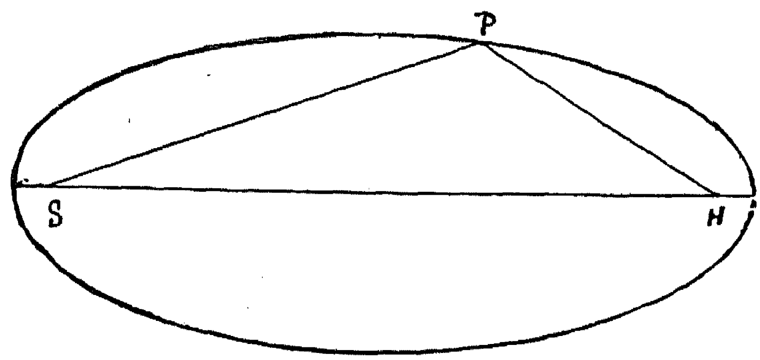
Tycho Brahe.—The Copernican system satisfied the observed planetary motions in broad outline, but for more accurate representation it was necessary to add a number of small epicyclic or eccentric movements. In 1546, a few years after the death of Copernicus, Tycho Brahe was born. Tycho became a great astronomical observer as contrasted with a theorist. The multitude and accuracy of his observations of the Sun, Moon and planets were destined to furnish the key by which the Copernican system was freed from the numerous subsidiary epicycles, etc., and the true movements of the planets discovered. Apart from particular discoveries, such as his determination that the comet of 1577 was more distant than the Moon,

and revolved round the Sun, Tycho's services to astronomy consist in the great improvements he made in astronomical instruments and in the accuracy of observations. He used his instruments with great skill, and also realized the importance of making long series of continuous observations.

Kepler.—Tycho's observations of Mars passed into the hands of his pupil and successor, Kepler, who, unlike his master, was a Copernican. For two reasons Mars is the most difficult of the planets for which to construct tables in harmony with the observations. As Mars sometimes comes near the Earth, its movements can be determined with great precision and any irregularities become apparent. Besides this, the orbit of Mars diverges more from the circular form than that of any of the other planets. A very complicated geometrical system of epicycles and eccentrics (pp. 21, 22) is required in order to represent the motion in satisfactory accordance with the facts.

Kepler tried hypothesis after hypothesis, but could not by systems of epicycles represent Tycho's observations with sufficient accuracy. He then tried other forms of curves, a daring innovation, as it was universally believed that the celestial motions must be composed of circular movements. Each different hypothesis involved an immense amount of labour, as all the calculations had to be started anew, and in Kepler's time there were no logarithm tables or other modes of simplifying numerical work. Finally, Kepler

tried the ellipse, and found that with the Sun in one of the foci he could adequately represent Tycho's observations. The ellipse is the curve which is obtained when a cone is cut obliquely. It may also be considered as the curve which a point P describes if it moves so that the sum of its distances from two points, S and H, remains the same. The two points S and H are called the foci. If they are a long way apart the ellipse is elongated or very eccentric; if close together it approaches more nearly to a circle. But Mars does not move uniformly in this ellipse, its velocity being greater when it is near the Sun than when it is further away. Kepler discovered how the velocity varies at different points in the planet's orbit.



Diag. XXII.

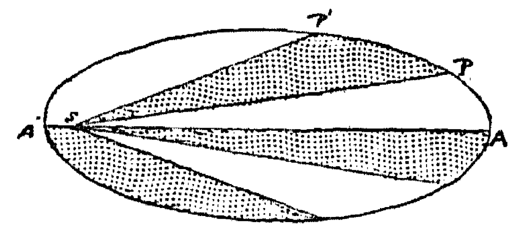
Kepler's Laws.—The results were stated in what are known as Kepler's first and second laws of planetary motion.

1. *The planets move in ellipses having the Sun in a focus.*

2. *The straight line joining a planet to the Sun sweeps out equal areas in equal times.*

Thus in Diagram XXIII a planet will describe the large angle A′SP′ in the same time as the small angle ASP, because the area A′SP′ equals the area ASP.

These famous laws were published in 1609. They were first established for Mars, and in course of time for the other planets, and even for the satellites which Galileo had found to circulate round Jupiter.



Diag. XXIII.

In 1619 Kepler discovered a third law which shows the relationship between the distance of a planet from the Sun, and the time it takes to perform a complete revolution. The more distant the planet the longer its period of revolution, but the planets do not move at the same rate: *e.g.* Jupiter is five times as far away from the Sun as the Earth, but takes twelve years, not five years, to complete its revolution.

Kepler's third law is—

The square of the time of revolution of any planet about the Sun is proportional to the cube of its mean distance from the Sun.

The meaning of this law will be clearly seen by inspection of the following table, in which a is the mean distance of a planet from the Sun, the Earth's mean distance being taken as 1, and T is the time in years of its revolution.

	Mercury	Venus	Earth	Mars	Jupiter	Saturn
a	·387	·723	1	1·524	5·203	9·539
a^3	·058	·378	1	3·54	140·8	868·0
T	·241	·615	1	1·881	11·86	29·46
T^2	·058	·378	1	3·54	140·7	867 9

The agreement of the figures in the second line with the corresponding figures in the fourth line constitutes the third law.

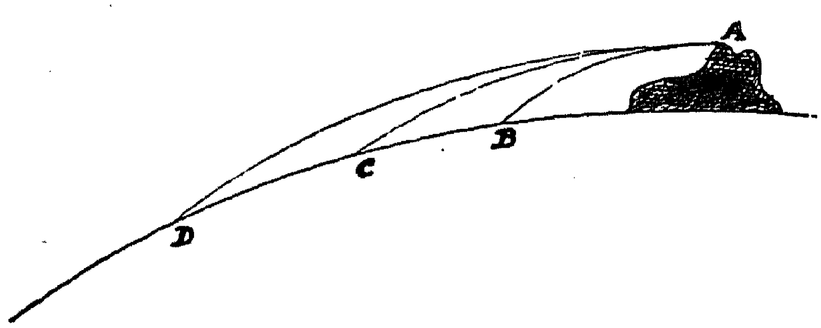
The Ptolemaic astronomy gave geometrical representations of the apparent movements of the heavenly bodies. The Copernican system gives their real movements. Kepler's laws, substituting the ellipse for the circle, gives these real movements with all the accuracy that Tycho Brahe's refined observations demanded, and are a concise statement of all the apparently complicated facts of planetary motion, as far as they had at that time been elicited by observation.

CHAPTER III

THE LAW OF GRAVITATION

Movement of Bodies in Curved Paths.—The science of dynamics, which may be said to have been founded by Galileo, led to further inquiry into the elliptic motion of the planets. Galileo investigated the motion of falling bodies on the Earth, and Huyghens showed under what conditions a body could revolve uniformly in a circle. Put very roughly, the condition is that the tendency to fly off should be counteracted by a pull towards the centre. For the Moon to revolve uniformly round the Earth in a circle, it is not necessary that it should be pushed in the direction of its motion, but it *is* necessary for it to be constantly pulled towards the Earth, otherwise it would move in a straight line. Since bodies on the Earth fall to the ground however high we may go, the Earth may be regarded as exercising an attractive force upon them. Might not this force continue to act, though to a diminished amount, at the distance of the Moon? Newton put this question to himself, and answered that if the attraction diminished according to the inverse square of the distance from the

Earth's centre, the Moon would move round the Earth in the circle it actually describes. As the Moon's distance is 60 times the Earth's radius, the diminution of the attraction according to the inverse square of the distance from the Earth's centre means that the attraction on a body at the Earth's surface would be diminished $(\frac{1}{60})^2$ at the Moon's distance. Newton compared the motion of the Moon to that of a bullet fired from the top of a hill. One fired horizontally from A with small velocity reaches the Earth at B; a second, fired with greater velocity, at C; a third at D. If the bullet could be fired with sufficient velocity it would not fall to the Earth, and if the velocity were exactly the right amount, the bullet would move round the Earth in a circle.



Diag. XXIV.

Movement in Ellipses.—Under what conditions will the planets describe ellipses round the Sun in accordance with the laws discovered by Kepler? Newton was able to answer this question fully. From the second law, that equal areas are swept out in equal times, he proved that the planets were subjected to attractive forces drawing them towards the Sun. From the fact that the path of a planet is an ellipse with the Sun in a focus, he showed that this force

varies inversely as the square of the planet's distance from the Sun. From Kepler's third law he showed that the Sun's attraction is the same for all the planets, the amount depending only on the inverse square of each planet's distance from the Sun.

Law of Gravitation.—In this way Newton was led to propound the law of universal gravitation that *every particle of matter attracts every other with a force which is proportional to the mass of each and inversely proportional to the square of the distance between them.* Thus, if at A there is a particle of matter whose mass is M, and at B another whose mass is m, and if the distance AB be called r, then each particle exerts on the other an attractive force which is proportional to $\frac{M \times m}{r^2}$. It does not matter what the particles are made of, or whether they are both on the Earth or both in the Sun, or one on the Earth and the other on Sun, Moon, or planets.

Diag. XXV.

Consequences of Law of Gravitation.—Newton now put forward the law of gravitation as an hypothesis whose consequences are to be deduced and compared with the observed phenomena of the solar system. Its immense range is seen from the variety of these consequences. Not only the movements of the Moon and planets, but the shape of the Earth and the planets, the ebb and flow of the tides and the preces-

sion of the equinoxes, were shown by him to be deducible mathematically from the law of gravitation. The verification of this law became one great branch of astronomy. Irregularities in the lunar and planetary motions have constantly presented new problems, which have been resolved as due to some consequence, till then unrecognized, of universal gravitation; while, on the other hand, the law has been confidently used to determine the condition of the solar system in past and future times.

Attraction of Spheres.—The total attraction of one body on another is made up of the attractions of each particle of one body on each particle of another. These are in varying directions and of various amounts. Newton was able to prove mathematically that spheres of uniform material or made up of concentric shells of uniform material attract one another just as if their masses were concentrated at their centres. This proposition would naturally be expected to hold for two spheres whose distance apart was much greater than their radii. Newton showed that it holds for all distances, and was thus able to calculate the combined effect of the attractions of all the particles which compose the Earth on a body at its surface, and thus verify that the law of universal gravitation gives a correct relationship between the attractive force observed in falling bodies at the Earth's surface, and that required to keep the Moon in its orbit.

Shape of the Earth.—In an expedition to Cayenne, in South America, near the equator, a French astronomer, Richer, found that a pendulum swung more slowly there than in Paris, thus showing that the force of gravity is less at the equator than in the latitude of Paris. Newton proved that this result necessarily follows from the law of gravitation, and that the Earth bulges out somewhat from the spherical form at the equator. If this were not the case, the water of the ocean would, owing to the Earth's spin, tend to flow towards and heap itself up near the equator.

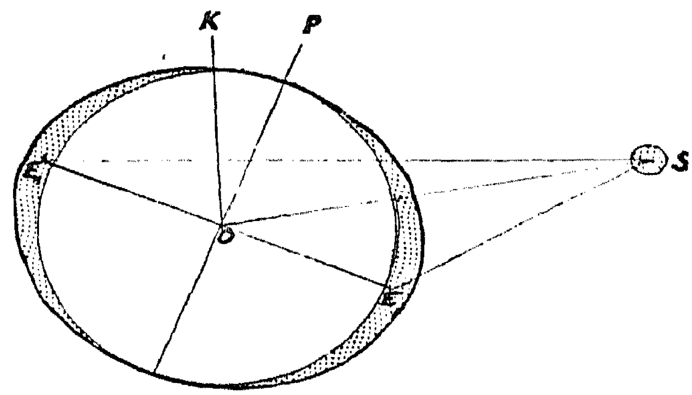
Tides.—Newton also gave a general explanation of the tides. The solid Earth, by virtue of its rigidity, responds to the attraction of the Moon *en masse*. But the actual attractive force varies somewhat from place to place according to the distance from the Moon. The result is that when the mean effect of the Moon's attraction is abstracted, there remains a force which tends to raise tides on the side of the Earth facing the Moon and also on the opposite side. The mobile water yields to this tide-producing force, whereas the Earth's rigidity prevents it from giving, and the water moves relatively to the Earth, producing tides. The occurrence of two tides a day is thus explained, for the water tends to rise at the points nearest to and farthest from the Moon, and as the Moon takes 50 minutes more than the 24 hours to complete its apparent revolution round the Earth, the time of high water is

50 minutes later each day. The attraction of the Sun also produces tides, but only half as large as those produced by the Moon. At New and Full Moon the forces exerted by the Sun and Moon combine, and spring tides occur, while when the Moon is in a direction at right angles to the Sun, their tide-producing forces are opposed, and neap tides result.

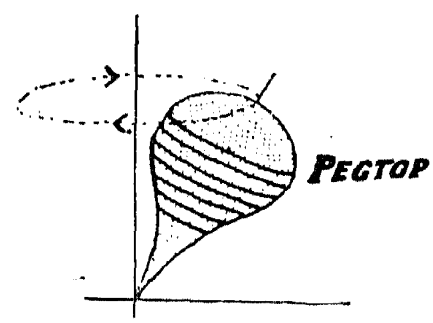
Precession of the Equinoxes.—The precession of the equinoxes, interpreted in the light of the Copernican system, means that the axis round which the Earth spins is not fixed in direction, but slowly changes. In 26,000 years it describes a cone whose axis is perpendicular to the ecliptic; the angle between the axis of the Earth and the axis of the cone is always $23\frac{1}{2}°$. In Chapter I this was expressed slightly differently, when it was said that the pole described a small circle of radius $23\frac{1}{2}°$ among the stars in 26,000 years.

Newton showed that this motion of the Earth's axis is a consequence of its oblate figure. In order to see the effect of the attraction of the Sun and Moon on the Earth, consider separately the sphere which can be just enclosed in the Earth, and the oblate part which bulges out at the equator. The attraction of the Sun, for example, on the spherical part produces a pull in the direction OS (Diagram XXVI), but does not tend to turn the Earth. The attraction on the nearer half of the part bulging out at the equator produces a pull in a direction ES, while the attraction on the more distant half produces a pull in the direc-

tion E′S. But as E is nearer to S than E′, the pull along ES is greater than that along E′S, and there result forces which tend to right the Earth, or bring OP nearer to OK. But when the dynamical consequences of this righting force are investigated, it is found that owing to the Earth's spin, the axis OP, instead of being moved nearer to OK, keeps at the same distance, but slowly describes a cone around it. This result may at first sight appear paradoxical, but a similar result from similar causes is familiar in the peg-top: while the top spins round its axis, the axis describes a cone about a vertical line and the top does not fall down as it would if it were not spinning.



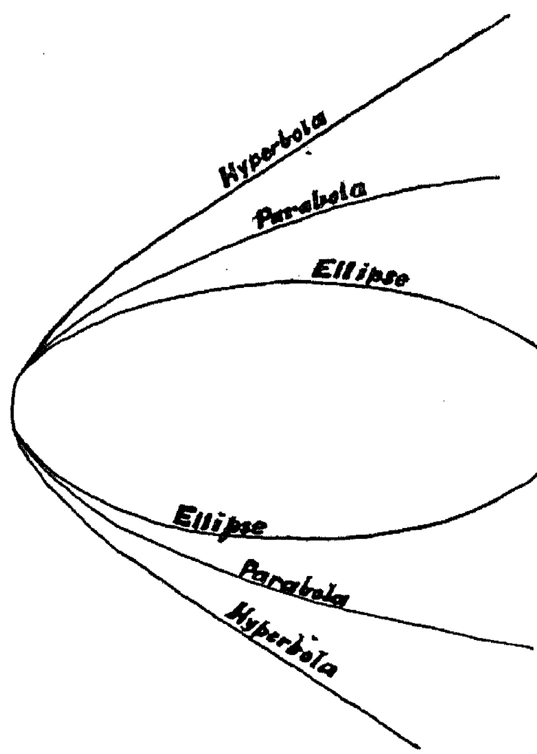
Diag. XXVI.



Diag. XXVII.

Comets.—The ellipse is not the only curve which a body can describe about another to which it is attracted by a force varying inversely as the square of the distance. If a cone be cut perpendicularly to its axis, we get a circle; if the plane is not quite perpendicular, we get an ellipse; as the plane of section becomes more inclined to the axis of the cone the curve becomes more and more elliptic, till when the plane is parallel to an edge of the cone the curve

is no longer closed, but becomes an open curve called a parabola, and at still greater divergence of the cutting plane from perpendicularity a curve called a hyperbola. The forms of these curves are shown in Diagram XXVIII. All these conic sections are possible paths for a body to describe about the Sun under the influence of gravitation. The planets describe nearly circular orbits. Newton showed that comets move in elliptic orbits of great eccentricity or in parabolic orbits. Thus comets are brought into the scheme of the solar system, and are seen to move like the Earth and planets under the dominating influence of the Sun's attraction.



Diag. XXVIII.

Masses of Heavenly Bodies.—A very interesting consequence of the law of gravitation is its application to determine the masses of heavenly bodies. If the mean distance between two bodies whose masses are M and m is a, and they revolve about one another in the time T, then the quantity $\frac{a^3}{T^2}$ is proportional to $M+m$, the sum of the two masses. By taking a to be the Moon's mean distance, and T the time in which

the Moon revolves, the formula may be applied to the Earth and Moon. By taking a to be the Sun's mean distance and T the year, it may be applied to the Sun and Earth. The Sun's distance is, let us say, 390 times that of the Moon, and the year is, roughly, 13 times as long as a sidereal revolution of the Moon. The combined mass of the Sun and Earth is, therefore, greater than that of the Earth and Moon in proportion of $\frac{390^3}{13^2}$. Thus the Sun's mass is 350,000 times that of the combined mass of the Earth and Moon. By taking a to be the distance of one of Jupiter's satellites and T the time in which it revolves round Jupiter, the formula is applicable to determine the mass of Jupiter. This is the astronomical method of determining the masses of the heavenly bodies. They are measured by the attractions they exert on one another, and these attractions are proportioned to $\frac{a^3}{T^2}$. The method has been applied to all the planets which have satellites and to double stars, when the distance between the two stars can be determined.

Disturbance produced by a third body.—The movement of two bodies under their mutual attraction was completely solved by Newton. When there are more than two bodies the problem becomes one of great difficulty. In the solar system the mass of the Sun is so preponderating that the movement of each planet

is very largely determined by the Sun. However, other planets influence the movement to some extent, and "perturb" the motion in an ellipse round the Sun as focus. Newton pointed out some of the effects, but in the main left this question to his successors. The Moon's motion is particularly difficult because, although the Sun is very distant compared with the Earth, its great mass makes its effect considerable. Newton showed how the rotation of the apse and the node discovered by Hipparchus were traceable to the Sun's action.

The "Principia."—Newton's discoveries, though many of them were made earlier, were published in the *Principia* in 1687. The doctrine of universal gravitation did not commend itself to the most eminent of Newton's scientific contemporaries. In 1738 Voltaire presented a popular account of it which procured its acceptance among French scientists. From that time till the early years of the nineteenth century the idea of universal gravitation was developed by great French mathematicians, who applied it in detail to all the movements of the solar system.

The task was one of extreme difficulty. The law of gravitation, which gives the forces that different bodies exert on one another, enables the rate at which the velocity of any body is changing to be calculated. When this is done, if the velocities are known at one particular instant, they may be found a minute later. In this minute the positions of the bodies have all

changed, the forces between them consequently altered, and the velocities are changing at slightly different rates. The difficulty consists in devising mathematical methods for duly integrating the effects of these varying forces. The greatest mathematicians have applied themselves to various branches of the subject, and gravitational astronomy has been a great stimulus to mathematics.

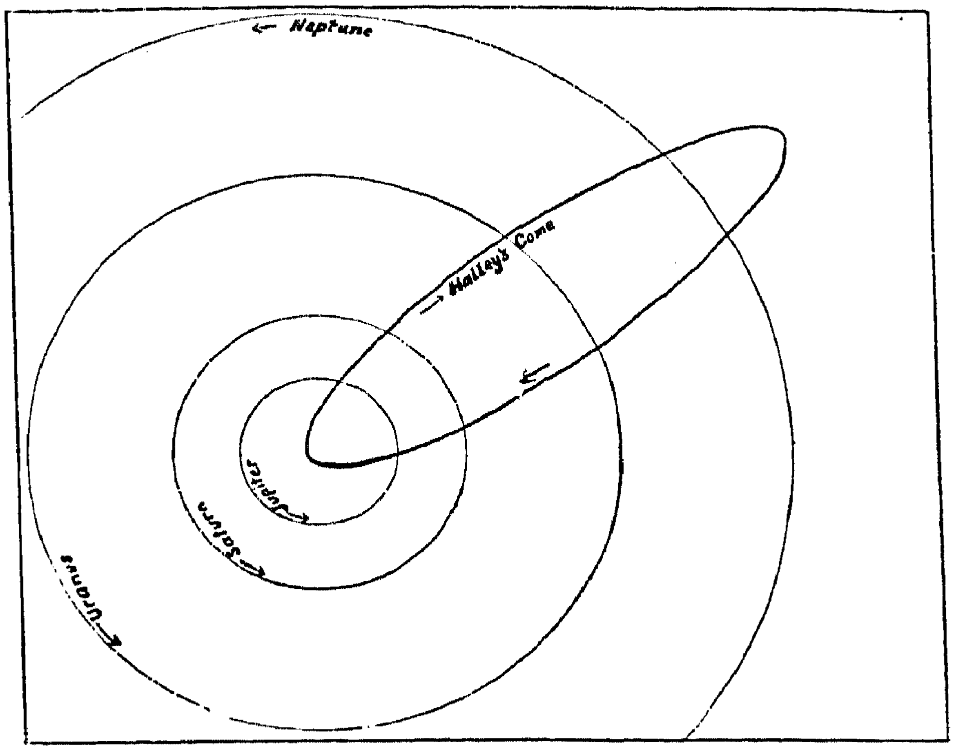
Stability of Solar System.—The work is of too technical a character for much of it to be referred to here. One important result may be mentioned. Laplace, the greatest exponent of gravitational astronomy since Newton, demonstrated the stability of the solar system. If the Earth were the only planet, it would perpetually repeat its path in the same ellipse. One effect of the attraction of the planets on each other is to slowly change each other's orbits. For example, the ellipse in which the Earth moves is at present gradually becoming more circular from this cause, and the plane of its motion—the ecliptic—is slowly changing. Laplace showed that the mean distance of each planet from the Sun remains unchanged, and that the eccentricities and inclinations of their orbits only suffer periodic changes, and these between comparatively narrow limits. Thus the action of the planets can never make the Earth's ellipse so eccentric that the Earth will at one part of its orbit approach very near to the Sun, and at the opposite part go to a correspondingly great distance

from it. Laplace showed that this result depends on the fact that the Earth and planets are all moving round the Sun in the same direction.

Discovery of Neptune.—In the year 1846, 160 years after the publication of the *Principia*, the law of gravitation led to the discovery of a new planet. Uranus, a planet beyond Saturn discovered by Herschel in 1781, did not conform exactly to its elliptic orbit. The perturbations caused by Jupiter and Saturn did not account for the anomalies in its movement. The possibility of an exterior planet being the cause was investigated simultaneously by Adams at Cambridge and Leverrier at Paris. From the researches of these two astronomers, the position in the sky where the disturbing body was to be found was pointed out. Search was made by Dr. Galle at Berlin, and the new planet (to which the name of Neptune was given) was duly found close to the predicted place.

Halley's Comet.—Another interesting episode connected with the law of gravitation is furnished by the history of Halley's comet. Halley made observations of a comet which appeared in 1682, and determined the position of its orbit. He found that the comet had moved in much the same path as the comets which appeared in 1531 and 1607. He concluded that these were the same comet; that this comet moves round the Sun in a very elliptic orbit, going to a distance of 33 times the Earth's distance from the Sun; and that the comet takes about 75

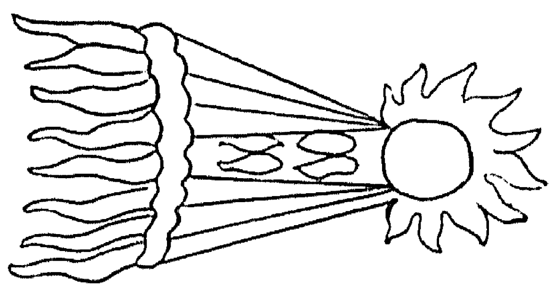
ears to complete its revolution, the time varying omewhat in consequence of perturbations caused by lanets near which it passes. The comet is only isible at its successive returns to the Sun when it is



Diag. XXIX.

comparatively near the Earth. Halley predicted its return for the year 1759. Before the reappearance of the comet, Clairaut, calculating the perturbing effects of the planets it had encountered in its path, predicted that the comet would be at the point of its orbit nearest to the Sun or at perihelion on April 13, 1759. The comet was discovered at the end of 1758, and Clairaut's prediction found to be only one month in error. It again returned to perihelion on Nov. 15, 1835, and its coming return in April 1910 was predicted by Messrs. Cowell and Crommelin of the

Greenwich Observatory with an error of only three days. The early history of this comet is interesting, as it has been identified with comets of which historic records are preserved. Diagram XXX, taken from the Bayeux tapestry, represents a comet which appeared in 1066, and was accounted an evil omen for King Harold. Calculation shows that Halley's comet in that year made one of its periodical visits to the Sun, and was unquestionably the one which was supposed to have predicted Harold's defeat and death. The comet's course has been traced back by Messrs. Cowell and Crommelin, and is almost certainly the one which Chinese records state to have been seen in 87 B.C., and possibly a still earlier one in 240 B.C.



Diag. XXX.

Movement of the Moon.—The determination of the Moon's movements from the law of gravitation has been a mathematical problem of great difficulty and complexity. The problem has a practical bearing, for if the Moon's position can be predicted with sufficient accuracy, it may be used to determine longitude at sea. In 1713 a prize of £20,000 was offered by the British Government for a method of finding longitude accurate to within half a degree. This prize stimulated the manufacture of chronometers on the one hand, and the formation of accurate lunar tables on the other. In 1765 £3000 was paid to the widow

of Tobias Mayer for his tables of the Moon—tables which gave the position of the Moon with an accuracy of about one minute of arc ($\frac{1}{30}$th) of the Moon's angular diameter.

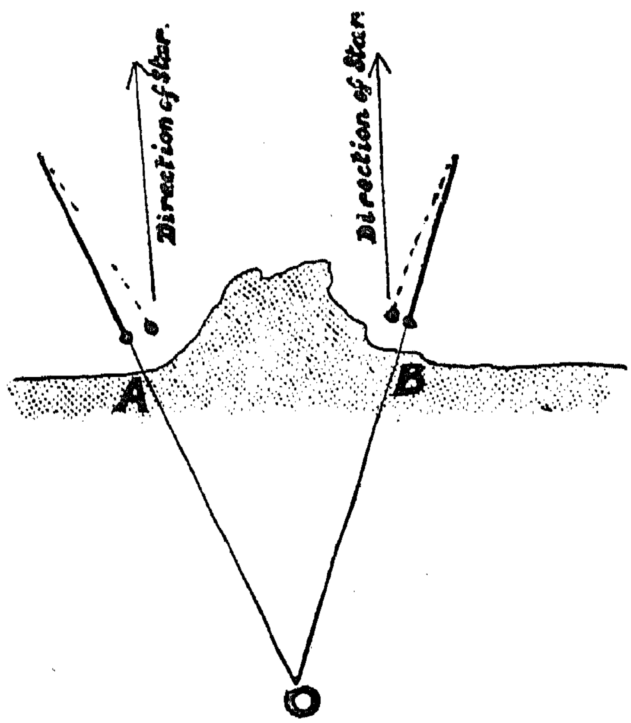
Theories of the Moon were developed with great mathematical skill by Clairaut, Euler, and Laplace, and various difficulties were removed, but a theory which will give the position of the Moon's place as accurately as it can be observed is required before the law of gravitation can be said to be completely verified. Elaborate theories of the Moon's motion have been worked out by many eminent mathematicians. At present Hansen's is used by the Nautical Almanac for the prediction of the Moon's place, and gives the position of the Moon for the period 1750—1850 with errors not larger than 1″ or 2″ (1″ is about $\frac{1}{1800}$th part of the Moon's diameter). As showing how complicated this question is, it may be enough to say that the final algebraic expressions which give the position of the Moon in Delaunay's Theory occupy a large quarto volume. Not only does the Sun affect the motion of the Moon round the Earth, but the planets, too, have their influence, both directly by their attraction on the Moon, and indirectly by their attraction on the Earth. The interest of the problem does not consist entirely in surmounting the mathematical difficulties but in determining whether, when all its consequences are traced, the simple law of gravitation is a complete key to these

very complicated movements. Compared with what has been already explained, what yet remains in doubt is trivial. Still, there are several curious differences between observation and gravitational theory in the motion of the Moon, and also of Mercury and Venus, of which the explanation seems at present to be a long way off.

Mass of Earth.—We have seen how the masses of the heavenly bodies can be compared with one another, the Sun with the Earth or Jupiter with the Earth, by comparing the movements their attractions produce upon bodies subject to their influence. But what is the mass of the Earth? This can be measured in several ways by comparing its attraction with that of a smaller body whose mass is known.

Attraction of Schehallien.—In 1776 Maskelyne compared the attraction of the Earth with that of the mountain Schehallien in Perthshire. As shown in Diagram XXXI, the effect of the attraction of this peak is to deflect the plumb-line towards it. The amount of this deflection is measured astronomically by observing the angle which the direction of a star makes with the plumb-line at two stations on opposite sides of the mountain. If there were no mountain, the angle between the plumb-lines at the two places would be the angle AOB, got by joining the places to the centre of the Earth. By measuring the distance AB this angle can be calculated. But owing to the attraction of the mountain

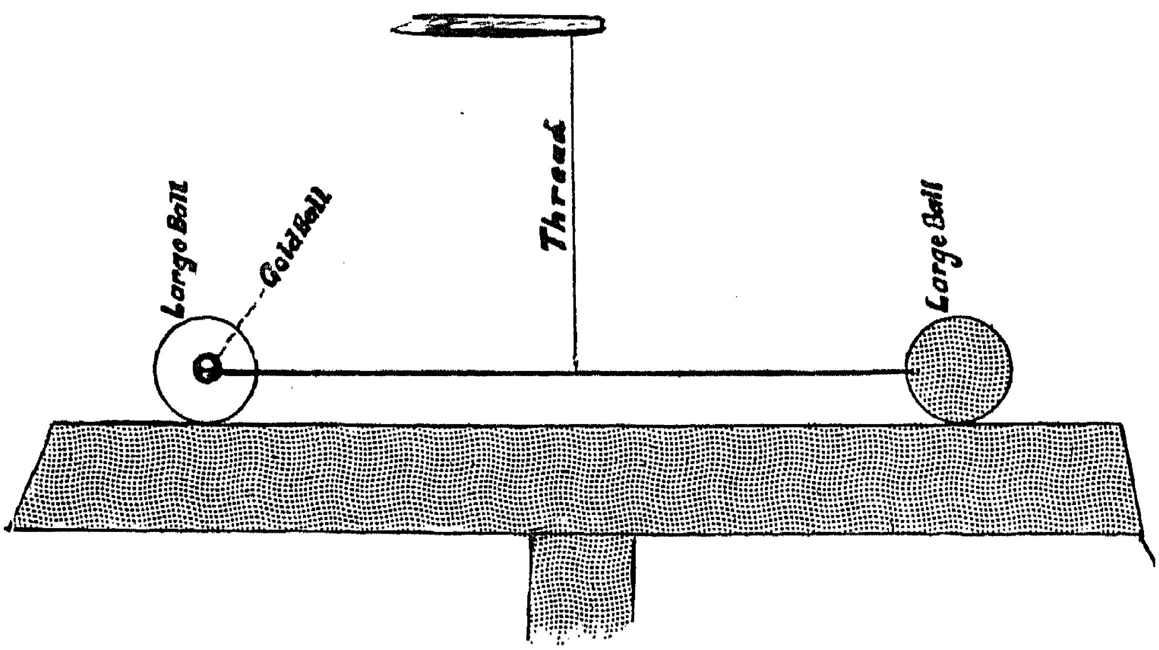
which pulls the plumb-line in different directions at A and B, the actual measured angle is found to be greater than the angle AOB. The amount of the excess is due to the pull of the mountain, which is thus compared with the pull of the Earth. In this way Maskelyne found the attraction of the Earth to be 4·7 times as large as it would be if the Earth were of the density of water throughout; or the Earth's mean density is 4·7 times that of water.



Diag. XXXI.

Cavendish Experiment.—A better and more accurate determination is obtained by measuring in a laboratory the attraction of a metallic ball on a small ball placed near it. This experiment was first made by Cavendish, and was carried out later with great skill by Francis Baily by means of a torsion balance. A light arm, at the ends of which are two gold balls, is suspended by a thread. Suppose the balls rest in a position due north and south. If two large balls are brought near them, on the east side of one and west of the other, the two gold balls will be attracted slightly, and the force of the attraction is measured by the twist given to the thread. This experiment

was carried out by Prof. Boys in 1893 in the cellar of the Clarendon Physical Laboratory at Oxford with the greatest precision. Observations were made on Sunday nights between midnight and 6 a.m., because at other times traffic over stony streets and shunting



Diag. XXXII.

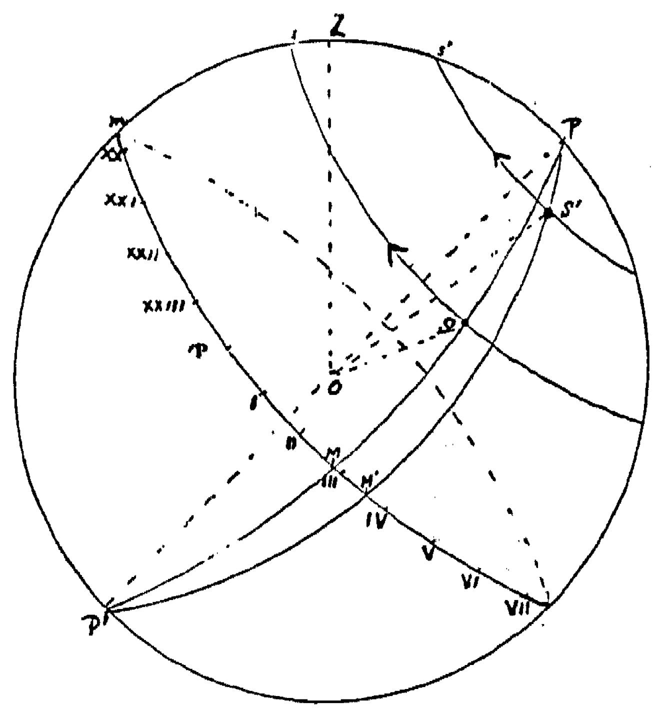
of trains set up tremors which interfered with the delicacy of the experiment. A fine quartz fibre held the balls, which were of gold, and in different experiments were $\frac{1}{5}$th and $\frac{1}{4}$th of an inch diameter. The large balls were of lead, and in different experiments varied from $2\frac{1}{4}$ to $4\frac{1}{4}$ inches in diameter. These experiments showed that the Earth's mean density is 5·5270 times that of water.

CHAPTER IV

ASTRONOMICAL INSTRUMENTS

THE stars appear to us as bright points fixed on a distant globe which turns uniformly. The first task of practical astronomy is to map their positions on this globe as accurately as possible. Instruments have gradually been evolved by which this mapping is carried out with ever-increasing precision.

Right Ascension and Declination.—It is first necessary to see clearly how positions on the celestial sphere are defined. Suppose P to be the pole, and that there is a star at S. The distance of the star from the pole is measured by the angle POS, or by what is the same thing, the arc PS of the sphere. The plane OPS will pass through P′, the other pole, and will cut the sphere in a circle. The circle 90° away from P (it is also 90° away from P′) is called the equinoctial or



Diag. XXXIII.

sometimes the equator. PS is called the *north polar distance* of the star, and SM the *declination*. If PS is known, SM is obtained by subtracting PS from 90°. If S is north of the equator the declination is positive, and if south negative. To know the position of S on the sphere, besides knowing SM, we need to know the position of M. A point on the equator called the First Point of Aries (♈), which moves with the stars, is used as the point from which to measure, and the arc ♈M (or the angle between the planes PO♈ and POM) is called the *right ascension*. The direction ♈M is measured in the direction contrary to that in which the Earth rotates, and may have any value from 0° to 360°. The point ♈ is not chosen arbitrarily, but is the point in the sky where the ecliptic or path of the Sun cuts the equator. It will be seen that this mode of defining the position of a star in the sky is similar to the method of defining a spot on the earth by its latitude and longitude.

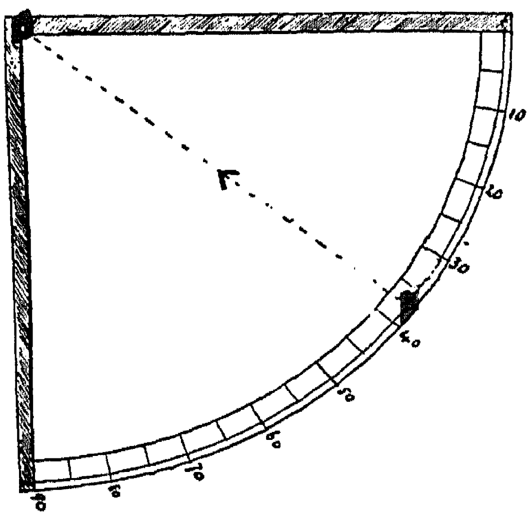
Now as the whole sky appears to turn about its axis in one sidereal day (approximately 4 m. shorter than the mean solar day which is used in ordinary life), the star moves in a circle completing its round in one sidereal day. At the moment when it is at *s* in the diagram, it is on a circle which passes through the poles and the zenith, or point vertically over the observer's head. This circle is the intersection of the celestial sphere with the meridian, or vertical plane which passes through the place of observation in a

direction exactly north and south. When S reaches s, its right ascension circle PSMP′ is PsmP′, or the point M has reached m. After a time another star S′ reaches the meridian at s', and M′ reaches m', and, if the interval of time between the meridian passage of S and S′ be measured, we shall obtain the angle of MM′ at the rate of 15° to one sidereal hour.

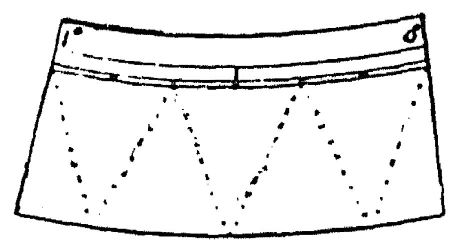
Clocks.—Suppose, now, we have a clock which reads 0 h. 0 m. 0 s. when ♈ is on the meridian, and is rated so that it completes 24 h. when ♈ returns to the meridian the next day. The time indicated by this clock when any star crosses the meridian gives the star's right ascension, at the rate of 360° to 24 hours, or 15° to 1 hour. It is frequently not necessary to change from time to angle, and the right ascension is taken as the actual time given by the clock (supposed to be correct). Thus it is very necessary for an observatory to possess such a clock, to divide up the time in which the Earth makes one rotation into 24 hours, 24×60 minutes and $24 \times 60 \times 60$ seconds. The time indicated by such a clock gives the right ascensions of all stars which are at that moment on the meridian.

Circles.—When a star is on the meridian its distance from the pole is the sum of its distance from the zenith and the distance of the zenith from the pole. In Diagram XXXIII $sP = sZ + ZP$. Now ZP is the same for all stars, and is obtained by subtracting the latitude of the place of observation from 90°. The direction of Z is the direction of a plumb line, so that

to find sZ it is necessary to observe the angle between the direction of the star and the direction of a plumb line. The method adopted by Tycho Brahe, though not invented, yet brought to a much higher degree of



Diag. XXXIV.



Diag. XXXV.

accuracy by him, consisted in having a large quadrant of a circle mounted on a wall which pointed accurately north and south (Diagram XXXIV). The arc of the quadrant was divided into degrees and further subdivided into minutes (as in Diagram XXXV). The direction of the star was taken along sights, one of which was at the centre of the quadrant and the other moved to the required position along the arc for the star to be seen. In this way Tycho Brahe observed the positions of stars and planets with errors of not more than 1′ or 2′.

The accurate graduation of the arc of a circle is an art which has been developed with the progress of astronomy. Quadrants fixed to a wall are no longer used, but complete circles attached to a telescope.

An accurately divided circle is as essential for the determination of declinations as a good clock is for that of right ascensions. The introduction of telescopes has not altered the method of determining the positions of stars. The right ascension of a star is still determined by observing the time at which it crosses the meridian, and the north polar distance from its altitude at this moment.

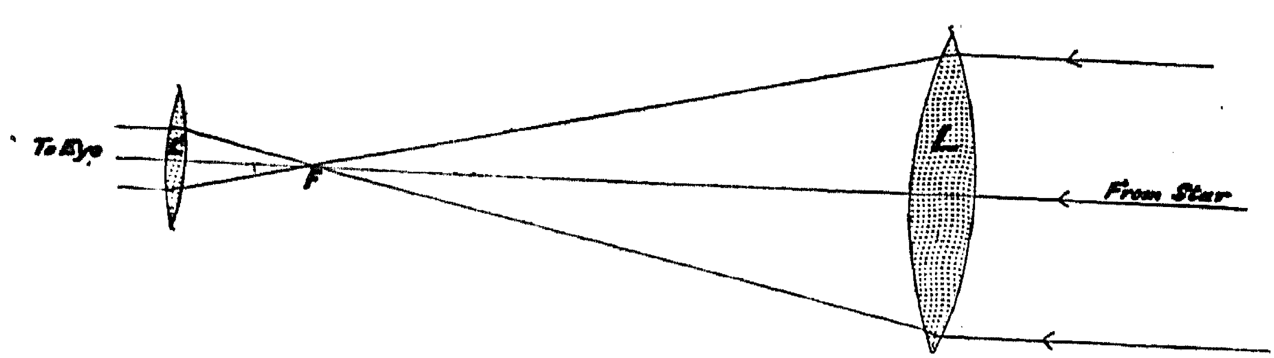
The Telescope.—The telescope has increased the accuracy and improved the power of the astronomical observer in a wonderful manner. It has three important properties—

(1) It increases the amount of light which enters the eye from a star, and thus enables fainter stars to be seen.

(2) It magnifies the apparent angle between two stars, and thus greater accuracy can be obtained in angular measurements.

(3) It obviates the necessity for the use of sights.

The light from a star comes to us in parallel rays. If these fall on a lens (Diagram XXXVI) their direc-

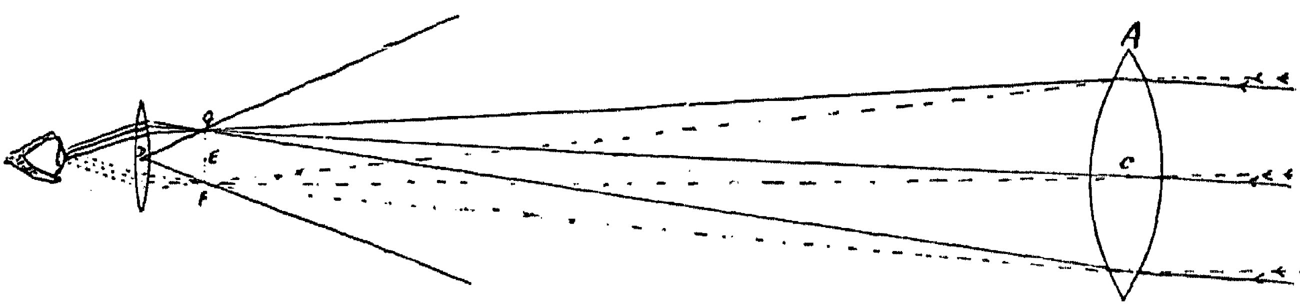


Diag. XXXVI.

tions are refracted so that they pass through a point F,

the focus of the lens. At F a bright point is formed, called the image of the star. If the rays which pass through F be intercepted by a second lens L′, they can be again converted into a parallel beam of light. If the diameter of the second beam is no wider than the pupil of the eye, all the star's light which fell on the lens L passes into the eye. The telescope, in effect, supplies the astronomer with an eye as big as its object glass and thus enables him to see very much fainter stars.

Now let there be two stars whose images are formed at F and G (Diagram XXXVII). The cone of light



Diag. XXXVII.

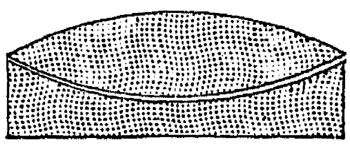
through F will be converted into a beam of parallel rays which, falling on the eye, will enable the star to be seen. Similarly the cone of rays through G will be converted into a parallel beam. The first beam is in a direction parallel to DF, and the second one parallel to DG. Thus the eye which receives these beams will see the two stars in directions parallel to DF and DG, whereas the actual directions are CF and CG. Thus the angular distance between the stars is magnified from FCG to FDG, which is in the proportion CE : DE, or that of the focal length of the

object lens to the focal length of the eye lens. Thus the longer the focal length of the object glass of a telescope and the shorter the focal length of the eye-piece, the greater the magnification.

Suppose the two lenses are firmly fixed in a tube, and in the focal plane FEG two pieces of fine wire or two spider's webs are stretched, crossing at E. When the telescope is pointed near a star an image is formed in the plane FEG. Shifting the telescope a little the image can be made to fall at E, the intersection of the two fine spider's webs. In this case the telescope is pointing accurately to the star, for the line EC then passes through the star. As E is fixed and C is fixed, the line EC serves the same purpose as sights at E and C; and it is much easier to secure accurate pointing in this way. This important improvement of the telescope was introduced by Gascoigne in 1640.

Refracting Telescope.—Telescopes have been gradually improved from the small and imperfect one of Galileo's to the large refractors and reflectors of the present day. A simple lens does not bring light of all colours to the same focus, and the image formed is consequently coloured and indistinct. Newton, who first resolved white light into a coloured band by means of a prism, supposed that this defect was irremediable. But in 1758 Dollond, an English optician, found that by combining a convex lens of crown glass (a dense glass with large refracting power) with a concave lens of flint glass (a lighter glass of less refractive power),

the defect can be largely remedied. The light from a star falling on the crown lens is refracted into a converging beam, and is also dispersed into the different colours of the spectrum: the concave lens of flint glass neutralizes the dispersion and makes the rays of different colours converge to the same point. This combination of lenses is called an achromatic object glass (Diagram XXXVIII).



Diag. XXXVIII.

It is not possible to completely banish all trace of colour in this way, and there are other imperfections arising from the fact that the curvature of the surfaces does not bring all parallel rays of the same colour absolutely to a point. These "aberrations," chromatic and spherical, are reduced to small dimensions by careful choice of the kinds of glass and by calculating the most appropriate curvatures for the surfaces of the two lenses. The single lens at the eye-end of a telescope has also been replaced by two separated from one another by a distance in suitable relation to the curvatures of the two lenses. In this way an increase in clearness is obtained in the parts of the image which are near the edge of the eye-piece.

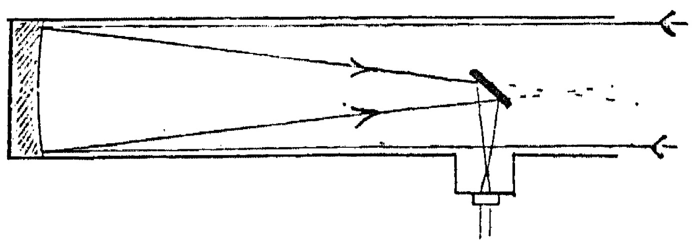
Before the invention of the achromatic object glass very long telescopes were used, because they gave greater magnification without much indistinctness from the confusion of colours. With an achromatic object glass much more magnification of the image

by the eye-piece is possible, and telescopes are not so cumbersome.

For a long time it was not possible to procure glass discs of sufficient uniformity and clearness to make object glasses of more than 3 inches in diameter. The largest object glass constructed by Dollond had a diameter of $3\frac{3}{4}$ inches. Early in the nineteenth century a Swiss artist, Guinand, succeeded in making larger discs. He was employed by Fraunhofer, who constructed object glasses of great perfection of 6 to 9 inches aperture. In 1840 a 15-inch object glass was constructed by Merz for the Imperial Observatory at Pulkowa; in 1870 a refractor of 25-inches aperture was made by Messrs. Cooke for Mr. R. S. Newall, and there are at the present time a considerable number of telescopes whose object glasses are as large or larger than this. The largest refracting telescopes are those of the Lick Observatory of 36-inches aperture, and of the Yerkes Observatory of 40-inches aperture, both made by the American opticians, Alvan Clark & Sons.

Reflecting Telescope.—In 1668 Newton made a small reflecting telescope which magnified thirty times. In this instrument the light from a star falls on a concave mirror of speculum metal—an alloy of copper and tin approximately in the proportions of four atoms of copper to one of tin. The light is reflected by the mirror so that parallel rays from a star are brought to a focus forming an image of the star. By the insertion of a small flat mirror, placed diagonally in

the tube, this image is shifted to the side of the telescope, where it can be viewed by an eye-piece (Diagram XXXIX). In 1723 Hadley, the inventor of the sextant, made a reflector with a mirror of $5\frac{1}{2}$ inches and a focal length of 62 inches with which a magnification of 200 times could be obtained. The great development of reflecting telescopes was made from 1776–1787 by Sir W. Herschel, who constructed specula of 6, 8, 12, 18, 24 and 48 inches, with focal lengths of 7, 10, 14, 20, 25 and 40 feet. These great telescopes were exceeded by Lord Rosse who, in 1848, constructed a reflecting telescope of 6 feet diameter and 53 feet focal length.



Diag. XXXIX.

In 1851 Liebig discovered a process of depositing silver on glass so as to give a highly reflecting surface. Since that time reflecting telescopes have usually been made of glass with a fine film of silver deposited on them chemically. The advantages are a more highly reflective surface, less weight, and the facility with which a tarnished silver film may be dissolved and a fresh one deposited without in any way interfering with the carefully figured surface of the glass.

Astronomy is greatly indebted to Dr. Common, an English amateur astronomer, for introducing the use of large silver-on-glass reflectors. With a 36-inch mirror he obtained in 1883 a beautiful photograph of

e Orion nebula. He completed in 1890 a mirror of feet diameter, and showed how to grind, polish and t a mirror so as to obtain the best results. The eatest living exponent of the art of making very ge mirrors is Mr. Ritchey, who has constructed tremely perfect ones for the Yerkes and Mt. Wilson servatories in America. He has recently constructed e of 60 inches diameter, and is now engaged on one 100 inches.

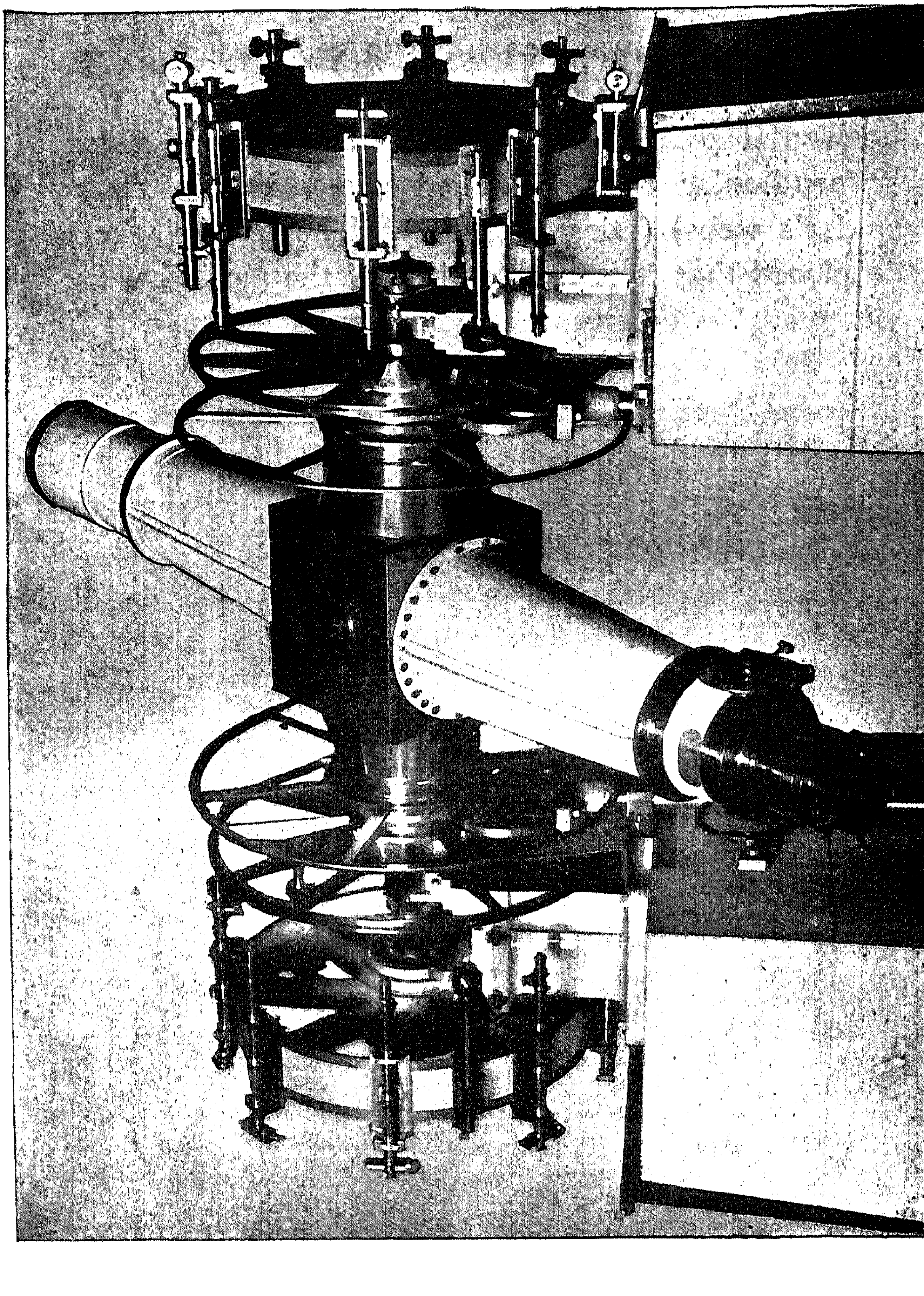
There has been throughout the long period of their velopment a friendly rivalry between the refracting d reflecting telescopes. The uses of the two instru-nts are now pretty well defined. Where accurate asurements are required the refractor is generally be preferred. Where the object observed is ex-mely faint the reflector has the advantage, for in portion to size reflecting telescopes are of much orter focal length, thus producing a smaller but ghter picture.

Mounting of Telescopes.—A small telescope, which is ed simply to look at the stars, can be held in the nds, but it will be found much easier to rest it on nething, and for one of moderate dimensions ne form of mounting which holds the telescope nly and yet admits of its being easily pointed to any rt of the sky is indispensable. When accurate asurements of any kind are to be made, the mount-g is a matter of great importance. There are two sses of observations for which the telescope is used,

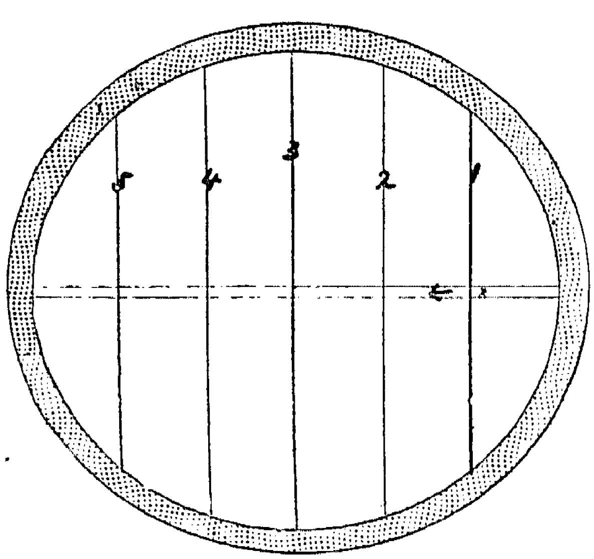
which require it to be mounted in entirely different ways. The actual position of the heavenly bodies in the sky may be required, as for instance in finding day by day the positions of the Sun, Moon or planets, or determining the positions of the stars. On the other hand, the position of the object in the sky may be of no interest, as in observations of the revolution of Jupiter's satellites about the planet or the rotation of Jupiter itself.

When the actual position of a star in the sky is to be determined, the telescope is fixed during the time of observation, and the star is watched as it moves in front of the telescope. The image of the star is seen as a bright point moving in the focal plane of the objective; in this focal plane spider's webs are stretched, and the observation consists in a determination of the exact position of the telescope, and the exact time at which certain threads are crossed by the star's image.

Transit-Circle. — The most important instrument of this kind is the transit-circle (Diagram XL). It applies the advantages the telescope gives in visibility, magnification and accuracy of sighting to the method used by Tycho Brahe of observing the time when a star crosses the meridian and its altitude at that moment. The telescope is fixed perpendicularly to a horizontal axis which ends in two accurately turned pivots. These pivots rest in bearings due east and west, so that the telescope can be turned to any point



in the meridian (or vertical plane pointing north and south), but is always confined to this plane. In the focal plane of the objective are two fairly close horizontal parallel wires and several equally distant perpendicular ones (so-called wires, but in reality spider's webs) (Diagram XLI). The middle wire is so placed that it is the "sight" of the meridian, *i. e.* when a star crosses the meridian its image will be seen in the telescope crossing the middle wire. A little before the time when a star should cross the meridian the observer turns the telescope about its axis to the right altitude. In due time he sees the star enter the field of his telescope, and moves the telescope so that the star may come accurately in the middle of the two horizontal wires. The star is watched as it moves and the exact time is noted when the several vertical wires are crossed. Formerly the timing was done by the observer listening to the beats of a clock, carrying the seconds in his head and estimating the tenths of seconds. An easier method now in general use is to register the time electrically on a chronograph, the observer pressing a button when the star crosses the wires. The mean of the times across these wires gives, subject to some small corrections which are



Diag. XLI.

easily calculated, the exact moment at which the star crosses the meridian, *i. e.* the right ascension.

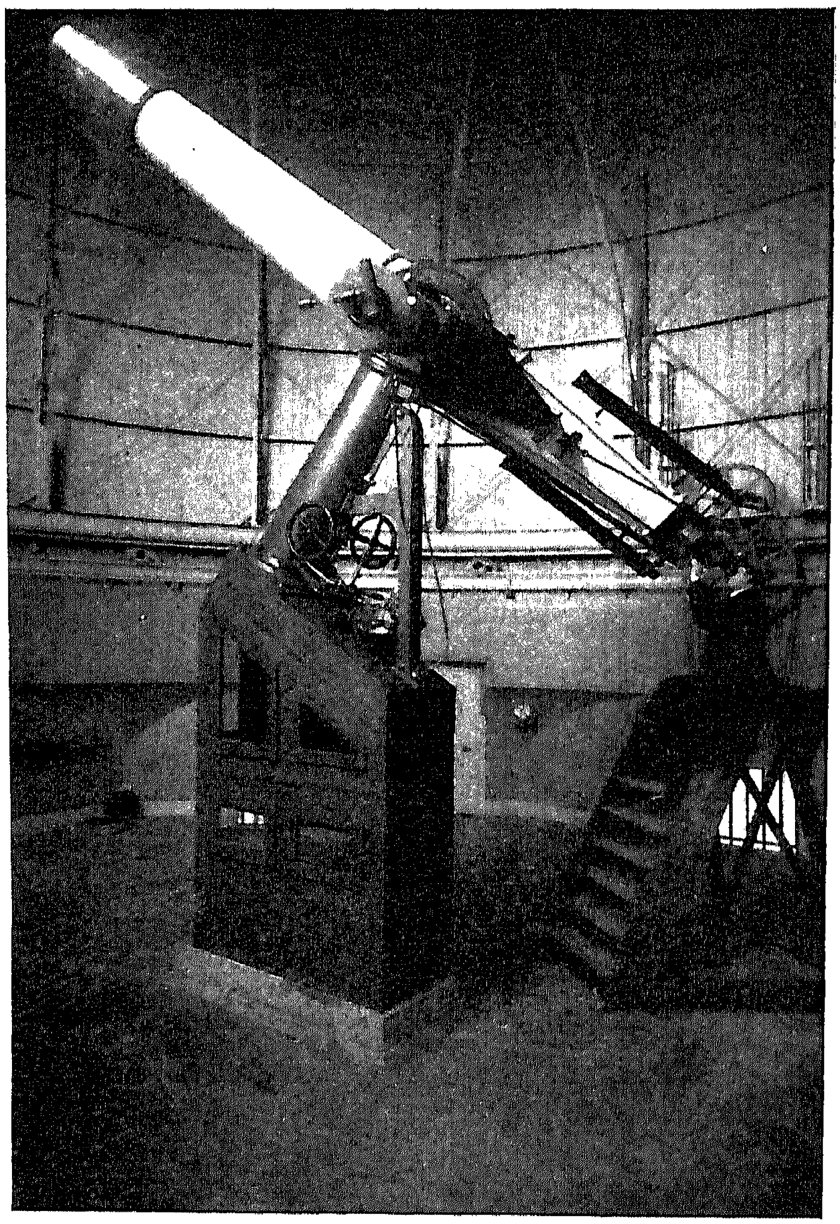
To obtain the star's declination it is necessary to determine the altitude at which the telescope is pointed. For this purpose a large graduated circle is fixed centrally on the axis of rotation of the telescope; the position of the telescope is determined by the particular division on the circle which comes to some fixed point. To secure greater accuracy microscopes are firmly fixed in positions for viewing the graduated limb of the circle.

In the focal plane of each microscope are placed wires, and the intersection of these wires will be seen between two divisions of the graduated circle. The exact distance of this point from a division is obtained by mounting the wires on a frame carried by a screw and reading the turns and fractions of a turn of this screw necessary to bring the cross to the nearest division of the circle. The divisions of circles are generally $5'$ apart (so that there are 12×360 on the whole circle), the fractions of $5'$ being read by means of the micrometer screw. For greater accuracy four or six microscopes arranged round a circle are used.

In actual practice there are a number of modifications and complications. With a good instrument, a good clock and good observer, the right ascension and declination of a star can be determined with an error which is seldom more than $2''$. To form an idea of $2''$ comparison may be made with the angular diameter of the Sun, which is $30'$ or $1800''$. By taking

the mean of several observations on different nights, stars' positions are found with greater accuracy.

Equatorial. — In order that a telescope may be kept pointing to a star as it crosses the sky the telescope must be given a suitable movement. The movement



Diag. XLII.

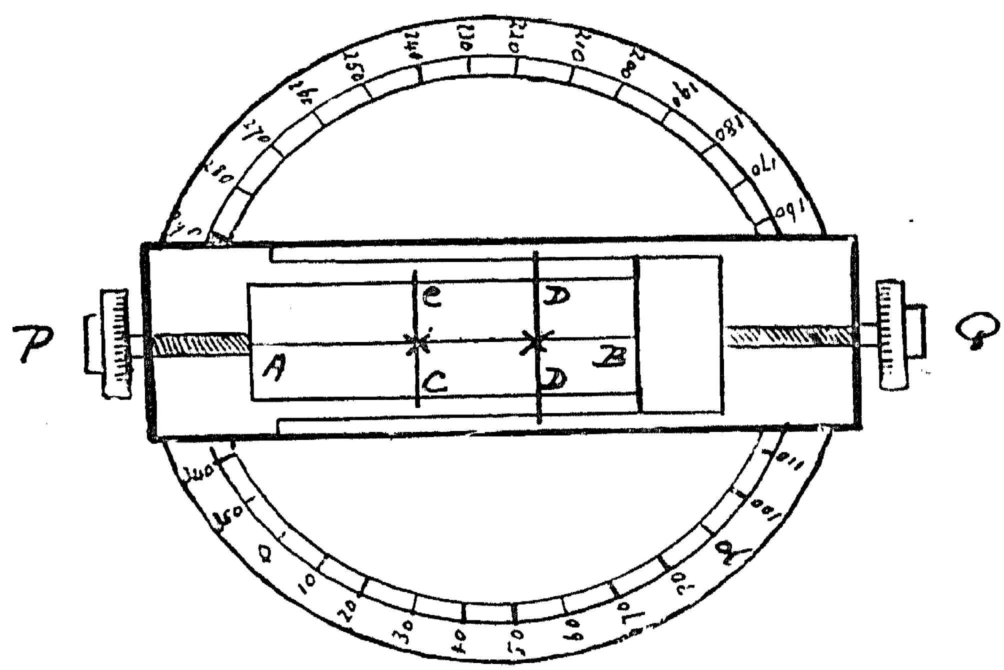
required is easily demonstrated by a pair of compasses. If one leg be pointed towards the pole, the other leg

can be opened out to an angle equal to the polar distance of the star; then by turning about the leg pointing to the pole the other leg may be brought to a position in which it points to the star. If now the compasses are turned uniformly around the leg pointing the pole so as to go completely round in one sidereal day, the other leg will point to the star all the time. This is exactly the principle of the equatorial mounting of a telescope. The telescope is perpendicular to, and can turn about, the declination axis. The declination axis is perpendicular to, and turns about, the polar axis (Diagram (XLII). The telescope is first placed in the required position and then turned by clockwork.

In the mounting of a large telescope there are necessarily many important details to be arranged in order to make it easy of manipulation and regular in its movement. It is also necessary to be able to correct for any want of precision in the driving clock, especially when the telescope must be kept pointing to the same part of the sky for a long time. These details are satisfactorily surmounted by the engineering skill of the instrument makers combined with care and patience of the astronomer who uses the equatorial.

Thus a picture of the part of the sky to which the telescope is pointed is formed in the focal plane of the object glass. By means of the equatorial movement this picture is kept at rest, and the observer looking through the eye-piece of the telescope can examine it.

Position-Micrometer.—This examination usually involves measurement of some kind, and other instruments are required for this purpose. For example, to measure the distance between two very near stars or the diameter of one of the planets, a micrometer of some kind is needed. A very simple form is the position-micrometer, which gives means of moving fine wires (webs of spiders stretched on frames) in the focal



Diag. XLIII.

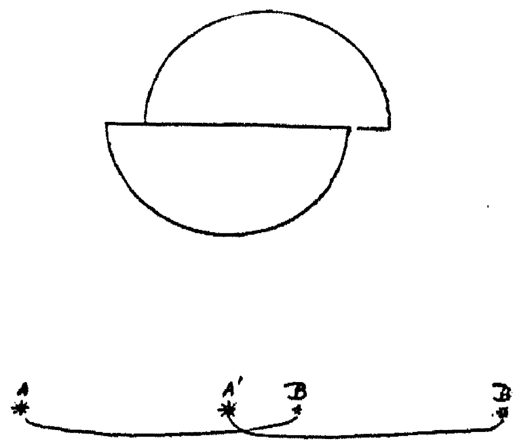
plane of the telescope. In Diagram XLIII, which represents this instrument, there are three lines, AB, CC and DD, of which CC and DD can be moved nearer or farther apart by means of screws P and Q, the distance between them being known from the readings of the screw-heads. In addition the micrometer, which is mounted in the telescope tube, can be turned to any required position. Thus if two stars

are in the field of view, by turning the micrometer and moving the screws, the intersection of AB and CC can be placed on one star and the intersection of AB and DD on the other.

The distance between the images of the two stars is measured in linear measure, let us say, in fractions of an inch; the angle between them is found by dividing this distance by the focal length of the telescope. Referring to Diagram XXXVII, the distance FG is measured, and to find the angle FCG it is sufficient to divide by the length CE, as we are only dealing with very small angles.

Heliometer.—A position-micrometer is suitable for measuring the distance between two stars which are so near that both can be seen at the same time. With a large telescope this means angles less than one minute of arc—or less than $\frac{1}{30}$th of the diameter of the Sun or Moon. For angles comparable in size with the Sun's diameter the most accurate visual observations are made with a heliometer. This is a telescope equatorially mounted, but having its object glass divided into two halves. The two halves can be moved, as shown in Diagram XLIV, by means which admit of the distance from the central position being accurately determined. Each half gives a picture of the part of the sky which is being observed; the two images are exactly alike, but they are at a distance apart equal to the separation of the two halves of the object glass. If, for example, two stars are looked at,

and the glass is turned so that the direction in which the halves are separated is parallel to the line joining the stars, there will be seen, as in Diagram XLIV, four images in a straight line, viz. A and B, the images of the two stars formed by one half of the glass, and A′ B′, the images formed by the other half. The halves of the glass are separated by a distance AA′ or BB′. If now they are still farther separated till A′ coincides exactly with B, the distance between the stars is exactly equal to the amount by which the two halves of the glass are separated. In practice a good deal of refinement is necessary in carrying out these observations, and it is, besides, a very delicate matter to cut an object glass in two. To instruments of this class we are largely indebted for the accurate measures by which the distances of the Sun and of the stars have been determined.



Diag. XLIV.

Photographic Telescope.—The telescope is seen in its simplest form when it is used for photography. A photographic plate is placed in the focal plane of the object glass or reflector, and gives a permanent record of the image formed there.

A reflector may be used for visual or photographic observations because the light of all colours is brought to the same focus, but an object glass to be used for

photography must be constructed so that blue light which affects the plates most powerfully is brought to a sharp focus, and not the red, green and yellow to which the eye is most sensitive. A photographic telescope is merely a large photographic lens of correspondingly long focus. Typical telescopes are those used in the International Chart of the Heavens, initiated at Paris in 1887, of about 13 inches diameter and 11 feet 3 inches focal length. The scale of these telescopes is such that the photographs of the Sun or Moon are about 1¼ inches in diameter. The field over which good pictures are taken has a diameter of about 5 inches. Using fast plates, stars visible to the naked eye require exposures of less than one second, and the number of stars shown increases largely with the length of the exposure. Long exposures are necessary to photograph very faint stars, and therefore the clock movement should be very accurate. If the telescope moves to follow the motion of the stars exactly their images will be round dots, but if it is moving too slowly or too fast they will be short lines. To secure the correct movement of the telescope arrangements are made for the observer to guide and control it.

When a photograph of the stars has been taken, it will contain a small number of bright stars whose positions are already known and a large number of fainter ones which are unknown. It therefore serves to fill in the fainter stars into a map on which the brighter stars are already delineated. Like the helio-

meter, a photograph can be used for finding the distances and relative directions of stars whose distance apart is less than one or two degrees.

We have so far considered astronomical instruments simply as means for the accurate measure of angles—the transit circle being typical of the methods by which the relative positions of stars distant from one another on the celestial sphere are obtained, and the equatorial mounting with its various adjuncts giving the relative positions of near bodies. But a telescope mounted equatorially can be used for many other purposes. For example, a photometer may be used, and the quantity of light received from different stars may be measured and compared. In one or two cases an instrument has been attached to the telescope by which the amount of heat received from the stars has been measured. But by far the most important instrument of physical research used by the astronomer in conjunction with the telescope is the spectroscope. When applied to the stars it is mounted on an equatorial telescope with the slit in the focal plane of the object glass. The telescope is so pointed that the image of a star may fall on the slit and part of it enter the spectroscope. The function of the object glass is to collect the light, and that of the equatorial to keep the telescope accurately pointed. The way in which a spectroscope analyzes the light which passes through it will be described in the chapter on the Sun.

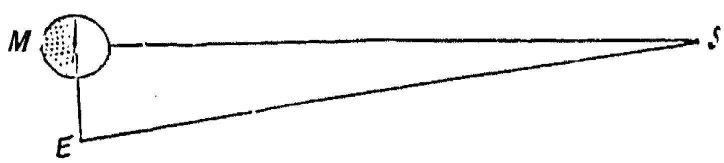
CHAPTER V

THE SUN'S DISTANCE

THE determination of the Sun's distance is one of the most important problems of astronomy. As we have seen, it is possible, by means of Kepler's third law, to determine the distances of the other planets from the Sun in terms of the Earth's mean distance. For example, the mean distance of Jupiter from the Sun is 5·2028 times the Earth's distance. A model of the solar system can be constructed, but till the Earth's distance from the Sun is found we cannot give the scale. More than this, the distances of the stars are determined in terms of the distance of the Sun, so that this is the standard length with which all astronomical distances are compared. Naturally such an important problem has received a great deal of attention.

A Greek astronomer, Aristarchus of Lamos, realizing that the Moon shone by reflected light from the Sun, argued that the Moon would be exactly half full when the directions of Sun and Earth, as seen from the Moon, were at right angles. Thus in Diagram XLV

the angle EMS is exactly a right angle. If the exact moment when the Moon is half full could be determined by observation, it would then be possible, by measuring the angle between the Sun and Moon, as seen from the Earth (the angle SEM of the diagram), to determine the exact shape of the triangle SME, and thus find SM in terms of EM. He found in this way that the Sun's distance was nineteen times that of the Moon. The method is extremely rough, because it is impossible to say exactly when the Moon is half full.

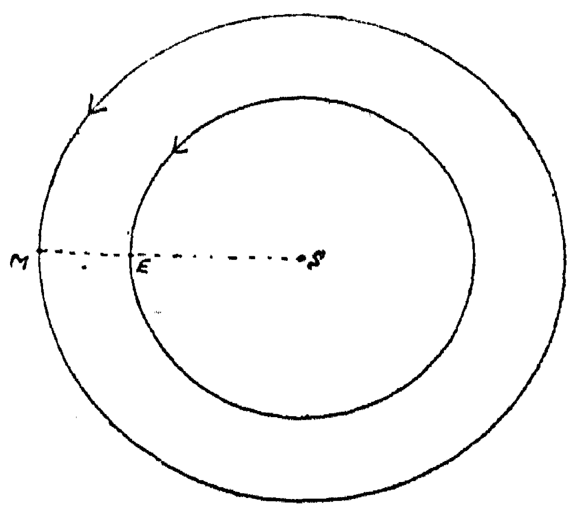


Diag. XLV.

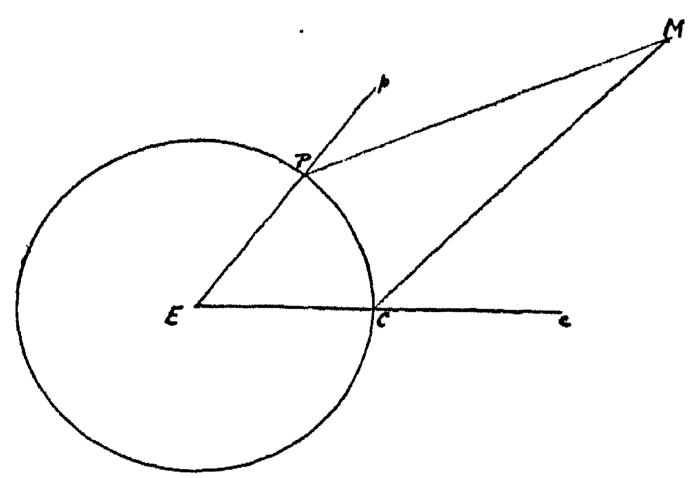
Till the time of Kepler this was the generally accepted distance of the Sun, but Kepler showed that it must be at least three times as far away.

Cassini's Measure of Sun's Distance.—The first determination which approaches to what we now know to be the distance was made by the French astronomer Cassini, between 1670 and 1680. He did not measure the distance of the Sun directly, but chose the planet Mars when in opposition, *i. e.* in a direction opposite to the Sun. Now, the Earth describes a circle of radius 1 about the Sun, while Mars describes one of radius $1\frac{1}{2}$, and therefore Mars, when in opposition, as at M (Diagram XLVI), is only at one-half the Sun's distance. The shorter distance is measured twice as easily. But more than this, Mars is seen at night with a background of stars, and its position can be deter-

mined very accurately in relation to these stars. Cassini sent out an expedition to Cayenne, and the positions of Mars were observed simultaneously from Paris and Cayenne. In Diagram XLVII, E is the centre of the Earth, EP*p* a radius through Paris, and EC*c* one through Cayenne, while M is the position of Mars. If at Paris the angle MP*p* is measured, and



Diag. XLVI.



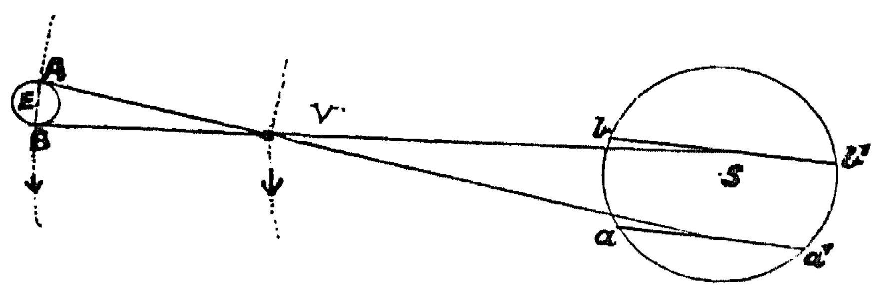
Diag. XLVII.

simultaneously at Cayenne the angle MC*c*, then, since the radii of the Earth, EC and EP, are known, and also the angle PEC from the positions of Paris and Cayenne on the Earth's surface, there is enough determined to draw the diagram accurately to scale, and thus find the distance EM. In actual practice the diagram would not be drawn to scale, but trigonometrical calculations made instead, but this is merely a substitute which avoids the difficulties and uncertainties of drawing the angles correctly.

Cassini's result was 84 million miles, and as we now know the distance to be 93 million miles, it will be

seen that he was within about 10 per cent. of the true value.

Transit of Venus. — Another and very famous method of determining the Sun's distance is by the transit of Venus. As the orbit of Venus lies within that of the Earth, it happens on very rare occasions that Venus passes between the Earth and the Sun, and is actually seen crossing the Sun's disc as a black spot. As at these times Venus is about 25 million miles from the Earth, while the Sun is much farther away, it follows that, seen from two points as distant

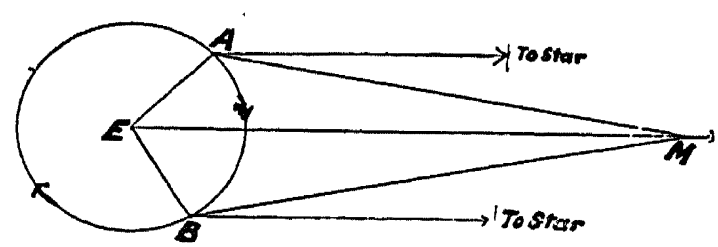


Diag. XLVIII.

from one another as possible on the Earth's surface, Venus traces a slightly different path across the Sun's disc. This is shown in Diagram XLVIII, but immensely exaggerated. By observations of the exact times at which Venus enters and leaves the Sun's disc at the two stations, it is possible to determine the distance apart in angle of the two chords *aa'* and *bb'* and thence to find the distance of Venus—the distance AB between the two stations serving as the base-line. Observations made at the transits of 1761 and 1769 gave the distance of the Sun 95 million miles. An

attempt was made at the transits of 1874 and 1882 to obtain the distance with greater accuracy. Extensive preparations were made, and many expeditions were dispatched by the governments of Europe and the United States. Although every care was taken, the expeditions were a comparative failure, owing to the impossibility of saying with certainty what was the exact moment at which Venus was seen touching the Sun's disc.

Mars near Opposition.—In the year 1877 Sir David Gill made observations of Mars near opposition from the island of Ascension. As the Earth turns round, bringing the observer from A in the early evening to B in the early morning (Diagram XLIX), the direction in which Mars



Diag. XLIX.

is seen changes slightly. Instead of observing Mars simultaneously from two different places on the Earth's surface, it was observed evening and morning from the same point—the point of observation swinging in consequence of the Earth's rotation from one side to the other of the direct line from the Earth's centre to Mars. Are there any means of measuring the angle AMB? If so, the distance can be found. Now Mars is seen projected on the sky in the midst of the fixed stars. These are so distant that they are seen in the same direction from all points of the Earth's

surface. Suppose there were a star exactly in the line of EM. As seen from A, Mars would appear to the right of this star, but when the Earth's rotation will have carried A to B, then it will appear to the left. Measuring the angular distances between Mars and the star, the angles MAS and MBS are found, and by addition the angle AMB. Then, as the length AB can be easily determined, the distance EM is calculated at once.

The geometrical principles underlying this are easy enough, but observations necessary to obtain a good determination of the distance must be of extreme accuracy. The angles to be measured are so extremely small that the slightest errors make a considerable difference in the result. The measures of angles were made with a heliometer, and errors arising from the instrument and the observer were guarded against, and where possible their effects eliminated by further observations. An additional difficulty is found in the movement of the planet. Mars does not stay still between evening and morning to suit the observer's convenience, so its motion has to be carefully calculated and allowed for. As Mars is near opposition for a considerable time, long series of observations are carried on night after night and morning after morning, and the final result derived from the mean of the whole series. Although a very accurate result was obtained, the fact that Mars has a disc of considerable size gave rise to a little uncertainty. It is much easier to

measure the distance of a bright point from another than to measure the distance of a bright point from the edge of a disc, where one is liable to measure from a little inside or a little outside of the edge. Now, there are among the small planets whose orbits are rather further from the Sun than that of Mars, some which, owing to the eccentricity of their orbits, come sufficiently near to the Earth for them to be available to determine the Sun's distance. From these Sir David Gill picked out Victoria, Iris and Sappho as being the most suitable, and made an extensive series of observations at the Cape of Good Hope in the years 1888 and 1889, and also secured the assistance of observers at northern observatories in the observations of the planets, and in the extensive subsidiary observations necessary to determine the positions of the stars from which the angular distances of the planets were measured. The details of the observations and the determination of the Sun's distance from them occupy two large quarto volumes. The final result is that the Sun's distance is 92,874,000 miles, and from the agreement between the different observations it is concluded that the error is probably not more than 50,000 miles. This error corresponds to an error of one yard in measuring a mile.

Eros. — On August 13, 1898, Dr. De Witt of Berlin discovered a small planet, to which the name Eros was subsequently given, which at times comes to within 14 million miles of the Earth. This small body, only

28 miles in diameter, is our nearest neighbour among the planets, and is admirably suited to determine the Sun's distance. At the end of 1900, when Eros came to within 30 million miles of the Earth, a very extensive series of observations was undertaken in co-operation by many observatories. The method employed was essentially the same as the one just described with regard to Victoria, Iris and Sappho; the main difference being that photographs of the planet and surrounding stars were taken, and afterwards measured, instead of the planet's distances from neighbouring stars being measured with the heliometer. The photographic telescopes employed were of long focus—from $11\frac{1}{4}$ ft. to $22\frac{1}{2}$ ft.—and consequently the photographs were on a large scale, and admitted of the accurate determination of the position of Eros among the surrounding stars. The result derived by Mr. Hinks of the Cambridge observatory from the combined observations of Eros is approximately 92,800,000 miles, agreeing very closely with the distance found by Sir David Gill.

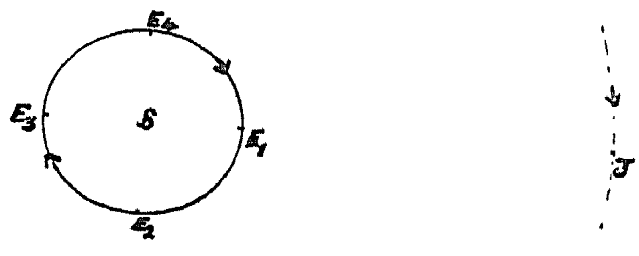
It should be noticed that the methods of determining the Sun's distance just described, though very complicated in the details which must be considered when a result of high accuracy is aimed at, are very simple in principle. The distance of the Sun is measured just as a surveyor might measure the distance of a tree on the opposite bank of a river. The difficulty arises from the fact that the astronomer

cannot obtain a base-line larger than the diameter of the Earth. This, in comparison with the distance of Eros, is very small, and gives a triangle with very long sides and a very short base. A small error in the determination of the vertical angle makes a large error in determining the lengths of the long sides of the triangle.

The distance of the Sun may be determined in an entirely different way by observing the time which light takes to travel across this distance, and again by comparing the velocity of the Earth in its orbit with the velocity of light.

Velocity of Light. — In the year 1675 the Danish astronomer Roëmer discovered that light is not transmitted instantaneously, but moves with a measurable, though very great, velocity. He was led to this discovery by observations of Jupiter's satellites. The Sun's light causes Jupiter to cast a shadow, and the satellites may be seen entering or emerging from this shadow. From numerous observations it became possible to construct tables predicting the times of these occurrences. Roëmer found, however, that when the Earth was near to Jupiter the eclipses occurred before the predicted times, but after them when the Earth was more than its mean distance from Jupiter. He explained these differences between the observed and predicted times by the difference of time taken by the light to travel a longer or shorter distance. Thus in Diagram L, if E_1, E_2, E_3, E_4, be four positions of the

Earth, S and J the positions of the Sun and Jupiter, the distances to be traversed in these four cases are E_1J, E_2J, E_3J, E_4J: and it is clear that the difference between the times taken to traverse E_3J and E_1J gives twice the time it takes for light to travel from the Sun to the Earth. The actual time taken by light to travel the mean distance between the Earth and Sun is 8 m. 18·5 s.

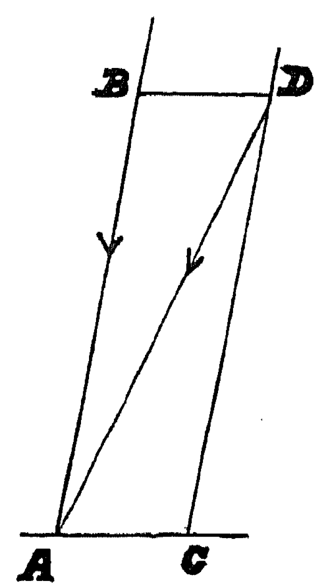


Diag. L.

Aberration. — Fifty years later, Bradley, while attempting to measure the distance of one of the fixed stars, γ Draconis, discovered the "aberration of light." He found that this star's declination changed in the course of the year. From December 1725 to March 1726 the star moved 20″ towards the south; it was stationary for a short time, and then moved northwards, reaching by the middle of June the position it had at the beginning of December. It continued to move northwards, till at the beginning of September it was 20″ to the north of its position in December and June. Again it was stationary for a short time, and then moved southwards, till at the beginning of December it was in the same position as in the previous year.

Although the movements of the star were exactly opposite to Bradley's anticipation, their regularity

showed that they were not accidental. At first Bradley looked for the explanation in a movement of the Earth's axis. But by making observations of stars in different parts of the sky he found that this could not be the cause, and after some other attempts he discovered that the velocity of the Earth in its orbit, combined with the velocity of propagation of light, afforded a complete explanation of the phenomena. A very familiar example will help to make this clear. If rain is falling vertically a person who is standing still holds his umbrella directly over his head, but if he is walking fast the rain appears to meet him, and he holds his umbrella slightly in front. In a similar manner, if the light moves over a distance equal to BA (Diagram LI), while the observer moves over a distance AC, the light will appear to come in a direction DA, instead of the direction BA. Let us further suppose that the gentleman with the umbrella walks round a circular track. When he is walking northwards his umbrella will be pointed a little to the north, when eastward a little east, when southward a little south—the direction in which he holds the umbrella being constantly changed. Now as the Earth is moving round the Sun its direction is constantly changing throughout the year. The direction from which the light appears to come from a star, *i.e.* the direction



Diag. LI.

in which the star is seen, is constantly changing—being always inclined slightly from the star's mean direction towards the direction in which the Earth at the moment is travelling, and in consequence the stars are seen to describe small ellipses in the sky about their mean positions. The semi-major axes of these ellipses are all the same, namely, 20″ (approximately), this being the angle of a right-angled triangle of which the longest side is proportional to the velocity of light, and the shortest proportional to the velocity of the Earth in its motion round the Sun.

Sun's Distance determined from Velocity of Light.—Roëmer's observations showed that light was propagated with a finite velocity, and Bradley's discovery of aberration was the first absolute proof that the earth revolved round the Sun. But in the middle of last century methods of measuring the velocity of light on the Earth were devised by Fizeau and Foucault; the method of Foucault by which the velocity of propagation of light is measured in a laboratory has been so perfected that Michelson and Newcomb have determined it as 186,330 miles a second, with an error probably not exceeding 25 miles. Knowing the velocity of light, if the time which light takes to travel across the Earth's orbit be accurately determined from the times of the eclipses of Jupiter's satellites, it is but a matter of simple division to find the radius of this orbit or the distance of the Sun. The accuracy

attainable by this method is considerable, but not nearly equal to that given by the trigonometrical methods described above.

The constant of aberration has been determined with very great accuracy by observation. This constant is the ratio of the Earth's velocity to that of light. Knowing the velocity of light, the velocity of the Earth is deduced, and from it the distance through which the Earth moves in a year, and then the mean distance of the Earth from the Sun. The value thus found for the Sun's distance is slightly greater than the result given on p. 92.

Quite recently another method has been employed for determining the ratio between the Earth's velocity and that of light. As will be explained in the next chapter, when the light from a star is analyzed by a spectroscope, the lines in the spectrum are slightly shifted towards the red or the blue if the source emitting the light and the spectroscope receiving it are moving away from or towards each other. This principle was applied by Sir William Huggins to determine the velocities with which stars are apparently approaching, or receding from, the Earth. Now, if the Earth's orbital motion is at one time of the year directed towards a star, it will six months later be directed away from it. At the first of these times spectroscopic observations give the velocity of the star away from the Solar System diminished by the velocity of the Earth in its orbit. Six months later they

give the velocity of the star added to the velocity of the Earth. The difference of the two results is twice the velocity of the Earth in its orbit. Thus we find how fast the Earth is travelling, and as we know that it completes its journey in one year, the length of that journey can be found, and the Sun's distance derived.

Gravitational Methods.—There are at least three other ways of determining the Sun's distance. One depends on the fact that the Earth every month describes a small circle about the centre of gravity of the Earth and Moon, and this slightly affects the direction in which we see the Sun. A second arises from the fact that when the Moon is between the Earth and Sun, the attraction of the Sun upon it is greater than when the Moon is on the side of the Earth away from the Sun. The effect of this can be traced in the Moon's motion, and leads to a determination of the Sun's distance. A third method depends on a disturbance which the Earth makes in the elliptic motion of Venus about the Sun: this leads to a determination of the Earth's mass, and through it of the Earth's distance.

The Sun's distance may therefore be found in a variety of ways. The methods may be classified as (i) surveyor's or trigonometrical methods applied to the nearest of the planets; (ii) methods which take the velocity of light as known, and compare the Earth's velocity with it, or else find directly the time light takes to travel the Sun's distance; and (iii) by

effects due to gravitation seen in the motion of the Sun, Moon, and especially of Venus, in which the Earth's distance from the Sun enters as a factor. The surveyor's or trigonometrical method applied to minor planets when nearest to us is the simplest, and at present gives the best results. But it is important to use as many methods as possible based on different principles in determining what is the astronomer's standard of length, in terms of which he measures all other celestial distances.

CHAPTER VI

THE SUN

WE think of the Sun as the centre and seat of government of the planetary system, and particularly as the source from which the Earth derives the heat and light required for the existence of man upon its surface. But we may also regard the Sun as a star much nearer to us than any of the others. For the stars are suns at such great distances that in the largest telescopes they appear to be only bright points. If the Sun were a million times as far away, we should see it as a star of the third or fourth magnitude in no respect specially remarkable. Owing to its proximity, a more detailed knowledge can be obtained of the Sun than of other stars, and it therefore serves as the sample by which we judge of them. Both on account of its relationship to our planet and ourselves, and of its being the representative of the millions of stars in the sky, the Sun is a supremely interesting subject for study and research.

Size.—When the distance of the Sun has been determined there is no difficulty in finding its size and mass. If we draw lines to two points at the opposite extremities of a diameter of the Sun, the angle between these

lines will be rather more than half a degree. It follows from this that as the Sun's distance is 93 million miles, its diameter is 865,000 miles, or about 110 times that of the Earth. Its volume will, therefore, be 110 cubed, or 1,331,000 times that of the Earth.

Mass.—The Sun's mass is determined from the effect of its gravitation. The Earth describes a circle of 93 million miles radius in one year. It follows that in one second it is pulled inwards from the tangent by $\frac{1}{100}$th of a foot. In Diagram LII, S being the Sun, E the Earth, and EG the distance travelled in one second, then FG = $\frac{1}{100}$ ft. Now the Earth's gravitation causes a stone to fall 16 ft. in the first second after it is dropped. At the Sun's distance the stone would fall $16 \times \left(\frac{4000}{93,000,000}\right)^2$ ft. = $\frac{1}{33}$ × one millionth of one foot.

Diag. LII.

Thus the Earth's attraction would only produce $\frac{1}{330000}$th of the effect produced by that of the Sun, and consequently the Sun is 330,000 times as massive.

Density.—As the ratio of the Sun's volume to that of the Earth is much greater than the ratio of their masses, it follows that the Sun is much less dense than the Earth. The figures are $\frac{330,000}{1,331,000}$ or about $\frac{1}{4}$. Now the Earth's mean density is $5\frac{1}{2}$ times that of water; therefore the mean density of the Sun is only $1\frac{3}{8}$ times that of water, or about half the mean density of rocks at the Earth's surface. The pressure inside

the Sun caused by the mutual gravitation of so huge a mass is enormous. The low density shows that the enormous pressures are accompanied by extremely high temperatures, and that the matter in the body of the Sun is in a gaseous condition.

Solar Radiation.—The Sun is constantly radiating its heat into space. A very small portion of this is intercepted by the Earth and planets. What becomes of the rest we do not know. The rate at which this radiation is proceeding can be measured by finding how much heat falls each minute on a given area exposed perpendicularly to the Sun's rays. An instrument for measuring the amount of heat received from the Sun is called a pyrheliometer. Such an instrument is constructed so that it shall retain all the heat which falls on it from the Sun, and it is shielded from receiving heat in other ways. As a great deal of heat is absorbed by the Earth's atmosphere, allowance is made for this, and when possible observations are made at a high altitude, such as Pike's Peak or the Gorner Grat, where less atmosphere has been traversed. The "solar constant" is the name given to the quantity of heat which would be received per minute on a square centimetre ($\frac{4}{10}$ inch $\times \frac{4}{10}$ inch) exposed perpendicularly to the Sun's rays if there were no atmosphere. Experiments show that this is 2·25 calories, or sufficient to raise the temperature of one cubic centimetre of water by 2·25° Centigrade.

If we imagine a sphere with the Sun as centre and a radius of 93 million miles, every square centimetre of the surface of this sphere receives each minute 2·25 calories. All this heat is radiated from the Sun's surface. Now the surface of the Sun is only $\frac{1}{46000}$th part of the surface of a sphere whose radius is 93 million miles. Consequently the Sun must radiate heat at the rate of $2{\cdot}25 \times 46{,}000$ calories per minute per square centimetre, or more than 100,000 calories. Every square centimetre of the Sun is turning out work at the rate of an 11-horse-power engine. Professor Young illustrates the immense output as follows:—*if the Sun were frozen over completely to a depth of fifty feet, the heat emitted is sufficient to melt the whole of this in one minute of time.* The mechanism by which this radiation is maintained is a constant flow of heated matter from the interior to the surface of the Sun, and a corresponding flow inwards of the cooled matter from the surface. Prof. Schuster gives an idea of the magnitude of the process as follows:—*In every second a fresh layer of hot gaseous matter will have to be brought to the surface, a layer a quarter of a mile thick if the gas is at atmospheric pressure.* And the matter brought up in the preceding second must be got out of the way when it has parted with all its heat.

Maintenance of Heat.—How is the Sun able to continue this prodigal expenditure of heat? It cannot be by combustion, for if the Sun were made of coal,

the heat obtainable would not be sufficient to maintain this expenditure for more than 6000 years, and geology teaches us that the Earth has been receiving heat from the Sun for millions of years. But every time a meteorite falls into the Sun it contributes heat, for the velocity of a body pulled into the Sun from a great distance will approach 400 miles a second, and the energy of such a body will by the collision be turned into heat. Though some heat is doubtless acquired by the Sun in this way, calculation of the amount shows that it is probably only a small percentage of the total. Helmholtz showed that the slow contraction of the Sun under the influence of its own gravitation would supply a much larger amount. This process is essentially similar to that by which a meteorite falling into the Sun contributes to its heat. In the case of a meteorite, the motion of a small body is checked suddenly. In that of the contraction of the Sun, a very large mass is continuously forcing its way inwards. In both cases energy acquired by gravitation is converted into heat. Helmholtz showed that if the Sun's radius contracted one mile in 40 years, sufficient energy would be obtained to supply the output by radiation. It would be thousands of years before such a small shrinkage could be detected. Still, this process cannot go on for ever, and if the Sun has no other way of replenishing its stores, the Earth will not continue to receive the amount of heat necessary for the

support of life on its surface many million years longer.

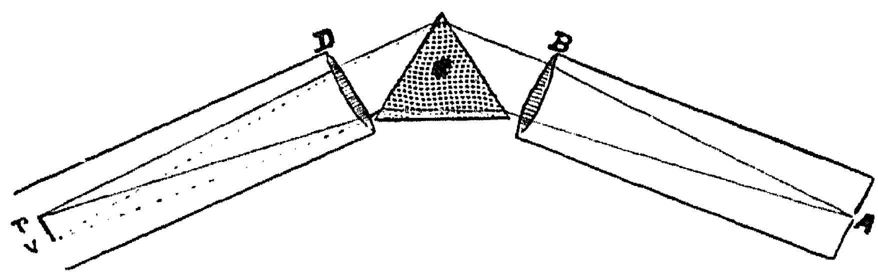
We may also ask how long the Sun has been radiating heat at this tremendous rate. Supposing the Sun to have been formed by matter falling together from very great distances, the supply of heat thus generated would be sufficient to maintain the present rate of radiation for 18 million years. We cannot say that this is the only way in which the Sun has obtained heat. It is known, as we shall see later, that helium exists in the Sun. Now, helium is formed from the disintegration of radium, a process which is accompanied with a great liberation of heat. The Sun's heat may have been partly acquired in this way, or in others of which we know nothing. It is generally believed by scientists that the Earth has been receiving heat from the Sun for a much longer period than 18 million years.

Temperature.—Very different estimates have been formed of the temperature of the Sun. It is seen to be very high because with a very powerful burning-glass all metals can be liquefied and vaporized. The difficulty in determining the temperature has been principally due to want of knowledge of the law connecting the amount of heat radiated with the temperature of the radiating body. In 1879 Stefan enunciated the law that the radiation varies as the fourth power of the temperature reckoned from absolute zero, or $-273°$ Centigrade. Messrs. Wilson and Gray heated a

definite surface of platinum electrically to a known temperature, and compared the heat radiated by this with the heat radiated by the Sun. Making necessary allowances for the amount of the Sun's heat absorbed in the Earth's atmosphere, they were in this way able to determine the Sun's temperature. The results formed by different observers agree in giving the temperature of the Sun at from 6000° to 10,000° Centigrade.

The Spectroscope.—During the last 50 years our knowledge of the Sun and stars has been extended in unexpected directions by spectrum analysis. Just as the ear can detect and separate several notes of a piano played simultaneously, so the spectroscope analyzes the vibrations which are transmitted in a beam of light. A beam of light may be, and often is, extremely complex, but by this analysis the different notes, so to speak, are separated, and a great variety of information is in certain circumstances obtained of the source from which the light proceeds. If a beam of sunlight be allowed to fall on a prism, it is split up into a coloured band in which the colours are arranged in the order violet, indigo, blue, green, yellow, orange, red. Each gradation of colour corresponds to a particular length of wave and time of vibration of the light—the whole consisting of an infinite number of different waves. A much more perfect analysis of a beam of light is obtained as follows: the light of the Sun (for example) is made

to pass through a very narrow slit A in the focal plane of an object glass B (Diagram LIII). The light falls on B and emerges as a parallel pencil of rays. This falls on the prism C, whose edge is parallel to the slit A. All the rays of any one wave-length emerge in parallel directions from the prism, and, falling on the object glass D, are brought to focus. The rays of each colour are brought to a different focus, and a coloured band *rv*, called a spectrum, is formed. When this experiment is carefully performed, the bright band is found to be crossed by a large number of dark lines.



Diag. LIII.

If, instead of sunlight, the light from a Bunsen burner in which some sodium chloride (common salt) is sprinkled is admitted into the spectroscope, two bright yellow lines are seen, and these two lines are coincident in position with two of the dark lines in the solar spectrum. The light from other substances when vaporized gives bright lines characteristic of the substances emitting them. The relation between the spectra of sunlight and of light from terrestrial sources was explained and developed by Kirchoff. He found that when sunlight streamed through a flame in which salt had been sprinkled into the

spectroscope, the yellow lines disappeared, being completely swallowed up by the solar dark lines which coincided with them in position, and which were much stronger than when the sunlight had not passed through the flame containing sodium vapour. He was thus led to explain the existence of the two dark lines in the solar spectrum which coincide in position with the yellow lines given out by the vapour of sodium, by saying that light from the hot interior of the Sun passed through a layer of lower temperature at the Sun's surface in which there was the vapour of sodium; that the sodium vapour in this layer absorbed the vibrations of the same period as those it could itself emit, just as a tuning-fork responds when its own note is played on a piano. He verified this proposition experimentally in his laboratory, by allowing light containing sodium vapour from a flame at a high temperature to pass through a flame at lower temperature also containing sodium vapour before entrance into the spectroscope. The yellow lines from the flame at lower temperature were darkened.

Spectra are of three kinds—

(1) *Continuous coloured bands* with no dark lines. These are given by the light emitted by glowing solids or liquids or gases subjected to great pressure.

(2) *A number of definite bright lines.* These spectra are obtained from glowing matter in a gaseous condition. They may be produced by volatilizing metals in flames or the electric arc; from an electric

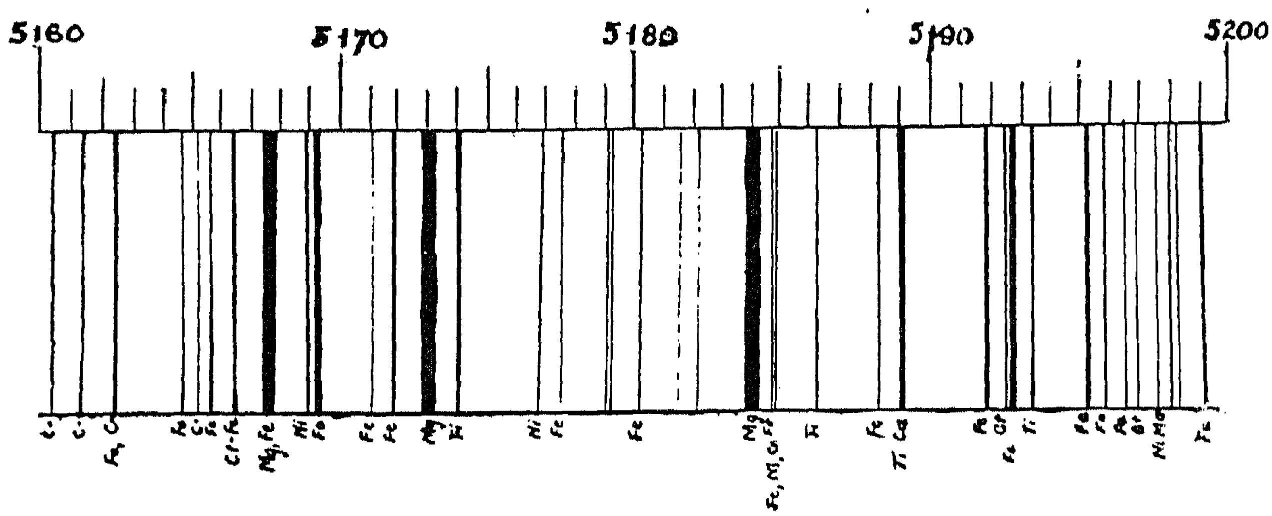
spark, in which cases matter from the terminals is carried across the gap between them; or by an electric discharge in vacuum-tubes containing a small quantity of such gases as hydrogen, nitrogen, etc.

(3) *Absorption spectra.* These consist of bright bands traversed by dark lines. They are formed when light from a source at higher temperature passes through a medium containing glowing vapours which would themselves yield a bright line spectrum. The spectrum is the reversal, dark lines for bright, of that which would be given by the medium through which the light passes.

Solar Chemistry. — Kirchoff's discovery was the beginning of solar and stellar chemistry. The spectrum of the Sun was carefully mapped by him, and the positions of certain dark lines shown to be identical with those in the spectra of sodium, calcium, magnesium, barium, iron and nickel. Sunlight has therefore traversed a layer surrounding the Sun in which vapours of these elements exist. To make sure of the exact coincidence in position of the solar lines and those of terrestrial elements it is necessary to spread out the spectra as far as possible. This is done by having a number of prisms instead of one, or, still better, by using a "grating" instead of prisms to disperse the light. A "grating" consists of a polished surface on which a large number of equally spaced parallel lines are ruled by a diamond. The art of ruling gratings was brought to great perfection by

Rowland of Baltimore. A typical grating of Rowland's is of speculum metal 6 inches long by 4 inches high, and on it are ruled 14,468 lines to the inch, so that altogether the grating contains 86,800 minute furrows. When light falls on such a surface, part of it is dispersed into a series of spectra.

With gratings of his own construction Rowland made a magnificent catalogue and map of the lines in the solar spectrum. It extended from the red end of the spectrum through the yellow, green, and blue far beyond the violet. The human eye is not sensitive to the rays of ultra-violet light, but the spectra can be photographed, as photographic plates are very sensitive to this light. Altogether he measured the intensities and positions of 16,000 lines and mapped them. Diagram LIV shows a small part of Rowland's



Diag. LIV.

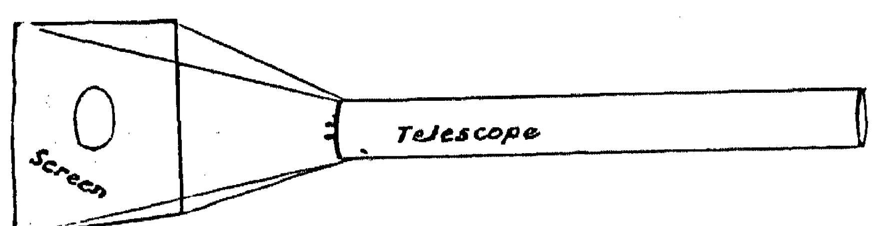
map in the green part of the spectrum, many very faint lines being omitted. The numbering gives the length of the waves of light belonging to that exact colour.

Thus 5160 stands for $5160/10^{10}$ of one metre, or, approximately, ·00002 of one inch. The chemical origin of the separate lines is given with them: C, carbon; Fe, iron; Cr, chromium, etc. By comparison with the spectra of terrestrial elements a very large number, in fact, nearly all the more intense lines in the solar spectrum, have been identified, and their origin traced to the existence in the Sun of some chemical element with which we are familiar on the Earth. More than 2000 lines in the solar spectrum arise from the presence of iron. The Sun contains hydrogen, oxygen; carbon, silicon; sodium, potassium, magnesium, calcium, strontium, barium; aluminium, chromium, iron, nickel, cobalt, manganese; lead, zinc, tin, copper, silver, palladium; titanium, vanadium; scandium, ytrium, zirconium, lanthanum, cerium, erbium, yterbium, europium, neodymium, gallium, and some other rare metals. The principal elements which have not been found in the Sun are nitrogen, phosphorus, sulphur, fluorine, bromine, chlorine and iodine, but, as Professor Rowland says, we cannot infer the non-existence of these substances in the Sun. In some instances their spectra do not contain any very strong lines, and their discovery is rendered difficult. It seems remarkable that rare metals, such as scandium, which it is difficult to procure on the Earth, should make their presence in the Sun so plainly visible.

It must be added that not all the dark lines in the

solar spectrum are caused by absorbing gases in the Sun's surface. The Earth's atmosphere in certain parts of the spectrum absorbs certain special rays and causes additional dark lines. These are mainly caused by oxygen and water vapour, and are specially prominent when the Sun at the time of observation is low, so that its light has traversed a long path in the Earth's atmosphere.

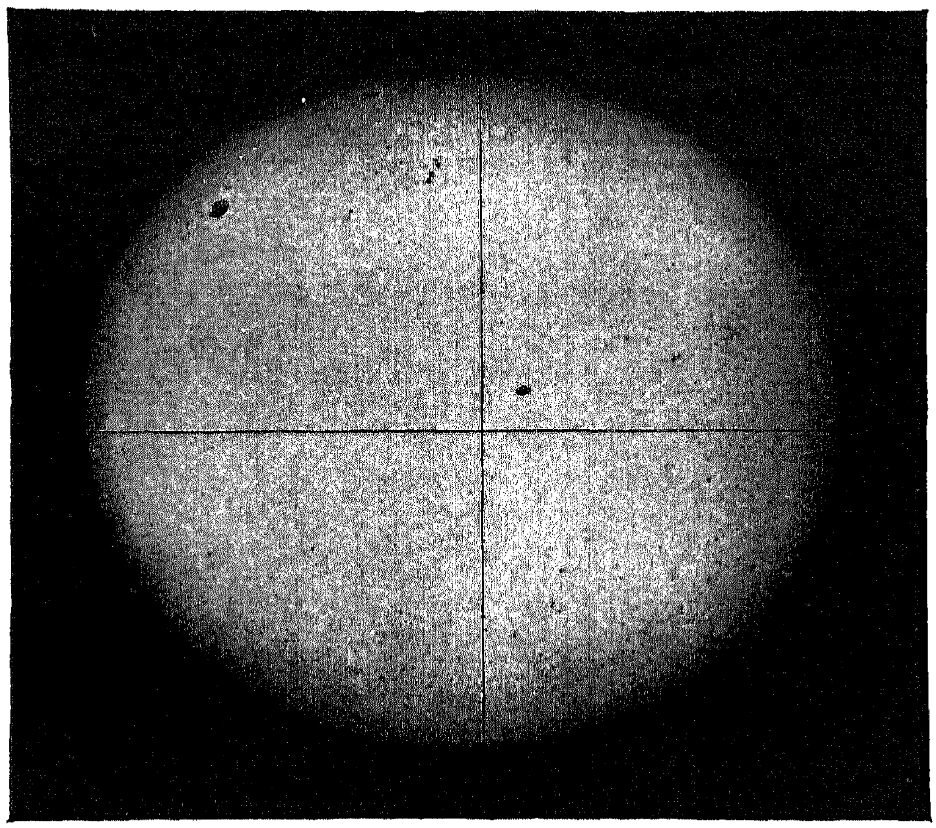
The Sun's Surface.—To observe the Sun at the telescope precautions must be taken by suitable eye-pieces to cut down a great part of the heat and light. The risk of accident to the eye may be avoided and an equally good observation obtained by drawing out the eye-piece of the telescope a short distance and projecting an image



Diag. LV.

of the Sun on a screen. This was the method adopted by Carrington, who made an extensive series of observations upon sun spots during the years 1853–61. It is more usual now to photograph the Sun, enlarging the image formed by the object glass by means of a second lens. Besides giving a larger picture, this has the advantage of diminishing the brightness of the image. Even then it is necessary to give very short exposures and to use very slow plates. Photographs of the Sun are taken daily at Greenwich, the

gaps caused by cloudy weather being filled in by photographs taken in India. A copy of one of the Greenwich photographs is reproduced here.

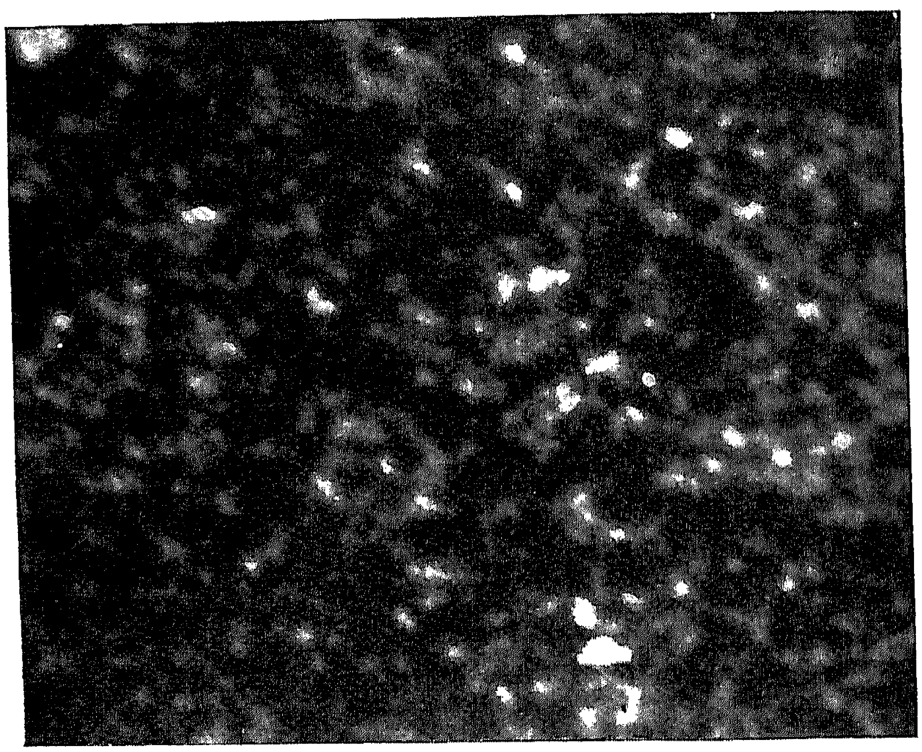


Diag. LVI.—Photograph of Sun.

This photograph shows that the light of the Sun is more intense near the centre of the disc than at the edge, pointing to an absorbing smoky atmosphere surrounding the photosphere, or luminous body of the Sun. The light from near the limb passes through a greater depth of this layer—just as near sunset on the Earth the sunlight traverses a greater extent of the Earth's atmosphere. This "dusky layer" absorbs violet and blue light to a greater extent than yellow

and red, and if it did not exist, the Sun, instead of being yellow, would have a bluish tinge.

Apart from the spots sometimes seen on it, the Sun's surface presents a mottled appearance. Nasmyth compared the appearances to willow leaves, Langley and Janssen to rice grains. These "rice grains" are of perhaps 400 miles diameter. They rapidly change their form. It is far from certain what they are.



Diag. LVII.—Granules on Sun.

Langley regarded them, and his view appears to be shared by Prof. Hale, as the tops of long columns in which the heated matter from the Sun's interior rises to the surface.

Observations of these curious granules have been made recently by M. Hansky, and still later by M. Chevalier. They found that on photographs taken

in quick succession individual granules could be recognized. They appeared to be moving about at random with velocities of from 5 to 20 miles a second. As M. Chevalier points out, it is difficult to believe that what we see arises from real horizontal movements. He compares the white granules to the summits of waves on a choppy sea. The white tops move, but the particles of water which form them are changing all the time.

Sun-spots.—Sun-spots were one of the first discoveries of Galileo's telescope. Occasionally a spot is large enough to be seen through dark glass with the naked eye. The best way of seeing them is to project the Sun's image, as explained on p. 112. The inner part of a spot, or *umbra,* is apparently black, and is surrounded by a greyer penumbra, but it must be borne in mind that a spot is only dark in comparison with the Sun. If the spot could be seen away from the Sun, it would be found to be brighter than an electric arc-lamp. Diagram LVI shows also near the limb bright patches, known as faculæ. These faculæ are always abundant near Sun-spots, and seem to be raised somewhat above the level of the photosphere. The nature of Sun-spots is a vexed question. They were for long supposed to be depressions in the Sun's surface, but this is not now regarded as at all certain.

When the spectra of Sun-spots are observed, it is found that, as compared with the solar spectrum, some lines are strengthened and others weakened.

These changes are doubtless due to the physical differences of pressure and temperature between spots and the generality of the photosphere, but their exact interpretation is not easy. Some recent observations seem to show that spots are of lower temperature. Titanium oxide was found in their spectra by Mr. Adams at Mount Wilson, and magnesium hydride by Mr. Fowler at South Kensington. The conditions of temperature and pressure in spots are therefore such as to admit of the formation of these compounds which do not exist in the photosphere. This certainly implies either a lower temperature or a higher pressure than in the photosphere, and has been generally interpreted as a sign of lower temperature. Some remarkable observations made by Prof. Hale in 1908 show that an intense magnetic field exists in Sun-spots.

Prominences and Chromosphere.—Reference has been made in previous chapters to eclipses of the Sun. At times the Moon is in such a position that it completely shuts out the view of the Sun for a few minutes from certain parts of the earth. These occurrences give opportunities of seeing the immediate surroundings of the Sun, which are generally invisible to us owing to the glare produced by the diffusion of sunlight in the Earth's atmosphere. A total solar eclipse discloses two remarkable features of the Sun, the prominences and the corona. The prominences are great tongues of flame which stand

out from the Sun's limb, sometimes reaching to such great heights as 50,000 miles. Diagram LVIII shows one which was seen in the eclipse of 1900. The most

Diag. LVIII.—Solar Prominences.

important feature of the prominences is that they give a spectrum made up of a number of bright lines, and not a bright band crossed by dark lines, like the Sun. This was discovered in the eclipse of 1868, and established the fact that prominences consist of luminous gases; and the identification of the lines showed that hydrogen was one of their main constituents. The French astronomer Janssen, who observed this eclipse in India, was so impressed by the brightness of these lines that on the day after the eclipse he again examined with his spectroscope the part of the Sun where he had seen a great prominence, and saw the bright lines in full daylight. He verified that a line in the red was coincident with one caused by hydrogen, and found a bright yellow line near to, but not quite coincident with, the position of the lines due to sodium. Sir Norman Lockyer, who was not at the eclipse, simultaneously discovered how these bright lines could be observed at all times, without waiting

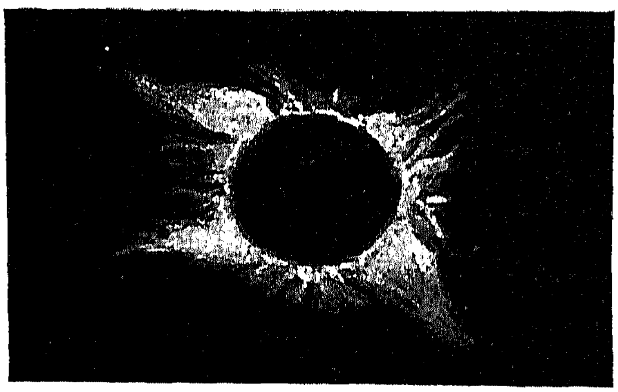
for the rare opportunities afforded by eclipses. The light which hinders these prominences from being seen with the naked eye being diffused sunlight reflected by particles in our atmosphere, its spectrum consists of a bright band crossed by dark lines. Sir Norman Lockyer argued that if he used a spectroscope of high dispersion, the diffused sunlight would be spread out into a long band of weak intensity, which would not obscure the spectrum of the prominences which is concentrated in a few bright lines. By bringing different parts of the Sun's image tangential with the slit of the spectroscope, the existence of a layer all round the Sun of the same constitution as the prominences was discovered. To this the name of chromosphere was given by Lockyer. When the study of prominences thus inaugurated was carried on regularly, it was found that prominences were of two kinds, quiescent and eruptive. Quiescent prominences are generally to be found on the Sun's limb; they change their form slowly, and are taken out of sight generally by the Sun's rotation. The eruptive prominences, on the other hand, shoot up with amazing rapidity, sometimes moving hundreds of miles per second.

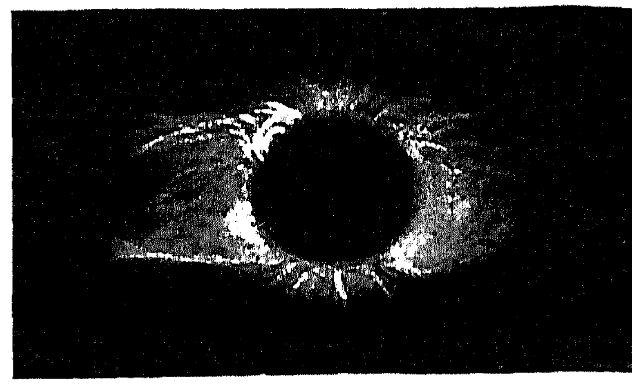
Although the chromosphere can be studied at all times, the moments of the beginning and ending of total eclipses are the most favourable. The chromosphere contains most of the elements found in the Sun, but there are differences between its spectrum

and that of the Sun which arise from the different physical conditions of the chromosphere and the part of the Sun below it where the absorption which produces the dark lines in the spectrum takes place. One interesting difference is the presence of bright lines due to helium in the spectrum of the chromosphere, whereas there are no dark lines due to helium in the solar spectrum. Reference has been made to a bright yellow line seen by Janssen near but not coincident with the lines of sodium. This line was found to be characteristic of the solar prominences and chromosphere, and the name helium was given to the unknown element which produced these lines. In 1895 Sir William Ramsay found this element in some terrestrial minerals, twenty-seven years after its presence in the chromosphere had been revealed to Janssen and Lockyer.

The Corona.—The corona is of an altogether different character from the prominences. While the latter rarely extend to more than one-tenth of the Sun's diameter from the limb of the Sun, the corona sometimes shows rays reaching to several diameters from the Sun. The instant an eclipse becomes total the corona is seen as an *aureole* surrounding the eclipsed Sun. It is of a pearly white colour, and brightest close to the Moon's dark limb. It is of a very complex form, which is only well shown by a series of photographs taken during the few minutes of total eclipse. A short exposure shows detail near the Sun,

while longer ones show the structure and extension at greater distances. Diagram LIX shows roughly the form of the corona in the eclipses of 1898 and 1901. When the nature of the corona is investigated by





Sun's Corona 1898. Diag. LIX. Sun's Corona 1901.

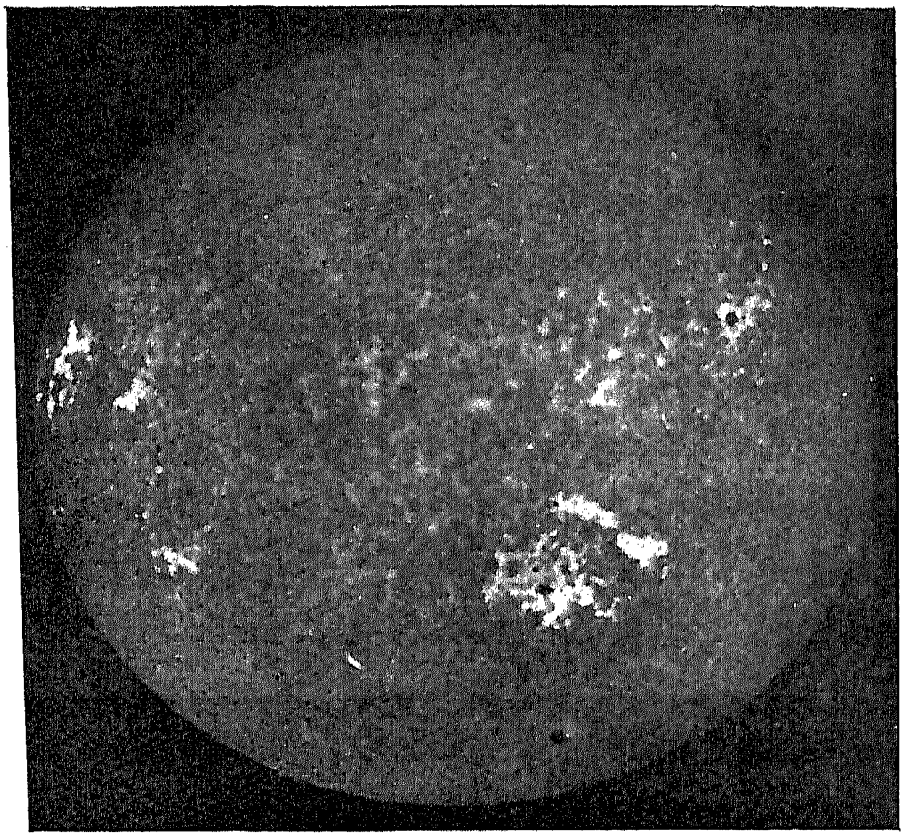
means of the spectroscope, a faint continuous spectrum is found such as would be given by incandescent solids or liquids, and also some bright lines caused by glowing gases. If the light of the corona were to any extent reflected sunlight, then its spectrum would be like that of the Sun, a continuous spectrum with dark absorption lines. But the existence of absorption lines like those in the solar spectrum has not been established, and we therefore cannot say that any considerable part of the light of the corona is reflected sunlight. The bright lines, of which more than a dozen are known with certainty, do not belong to any element with which we are acquainted. The name coronium has been given to the element which produces a very prominent line in the green part of the spectrum. Like helium, this

may be discovered on the Earth, but at present, at any rate, it is unknown.

The Spectroheliograph.—The photography of prominences in full daylight has been developed by Prof. Hale and M. Deslandres. The instrument by which this is accomplished is called the spectroheliograph. A prominence is photographed by excluding all light except that of some definite wave-length which is specially characteristic of the prominence itself. Thus a photograph may be taken in the light of C—the red line of hydrogen—and such a photograph will show the prominences as far as they consist of hydrogen. Similarly, a photograph can be taken which shows the forms of the prominences as far as they consist of glowing calcium.

The spectroheliograph has been developed further so as to photograph not only the limb of the Sun, but the whole face of the Sun in the light of one particular wave-length. Special interest attaches to the photographs taken in the light of K—a line in the violet due to calcium vapour. In the photograph of the Sun on p. 113 the faculæ are seen near the Sun's edge. The spectroscope shows that these faculæ are associated with glowing calcium vapour. When a photograph (of the Sun) is taken in K light, a picture is obtained of the calcium clouds over the photosphere. Such photographs were found to show more than the faculæ, and the name flocculi (fleeces) was given to them by Prof. Hale. The illustration (Diagram LX),

taken from one of Prof. Hale's photographs, shows how widely these flocculi are distributed over the whole Sun.



Diag. LX.—Calcium Flocculi.

The structure of the Sun is thus seen to be extremely complicated. The lowest part emits a continuous spectrum; this passes through an absorbing layer which gives the dark Fraunhofer lines. Next there is a dusky layer which cuts off a great deal of the light, the existence of this layer being shown by the diminishing brightness of the Sun as we go from the centre to the limb. Above these are the flocculi, or clouds of calcium. Then we come to the chromosphere with its bright line spectrum, and outside this

we have the corona. In addition, there are the more local phenomena of spots and faculæ and of the prominences rising out of the chromosphere.

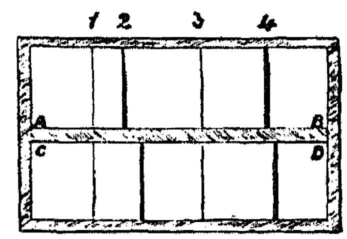
There are still two points with regard to the Sun which should not be omitted even in such a short sketch as the present, namely, (1) its peculiar law of rotation, and (2) the periodic fluctuations in the number of spots and associated phenomena.

Rotation of Sun.—Galileo found from the movement of spots across the Sun's disc that the Sun rotates. Prolonged examination of the spots shows its axis to be fixed in direction, but not perpendicular to the ecliptic. We therefore see the Sun under a slightly different aspect at different times of the year. The axis is inclined at an angle of 7° to the perpendicular to the ecliptic. From June 3 to Dec. 5 the plane of the ecliptic is north of the Sun's equator, and thus for this half of the year the Sun's north pole is on the visible side of the Sun, and in the other half of the year its south pole is visible. Between 1853 and 1861 Carrington made an exhaustive study of the movements of Sun-spots. He found that the Sun does not rotate as a solid body would, but that the period of rotation is greatest on the Sun's equator and diminishes as the poles are approached. At the equator a complete revolution occupies 24½ days, but at 30° from the equator 26½ days. As Sun-spots do not occur at great distances from the equator, the slowing of the time of rotation could not be observed

in this way to greater distances than 45° north and south of the Sun's equator.

In 1891 Prof. Dunér determined spectroscopically the law of the Sun's rotation in different latitudes between the Sun's equator and 15° from the poles. The spectroscope enables the motion of bodies to or from the observer to be determined. The position of a line in a spectrum is determined by the number of vibrations per second which light of that exact colour executes. If the source of the light is moving towards the observer or the observer towards the source of light, more than the normal number of vibrations reach the observer each second. The position of the line in the spectrum is shifted slightly towards the blue. The amount of shift is a measure of the ratio of the relative movement of observer and object to the velocity of light. A similar phenomenon takes place with regard to sound. If a horn were being blown on a railway train which was rapidly approaching a station, then to a person in the station the note of the horn would be slightly raised. This principle (called Doppler's principle) was first applied astronomically by Sir W. Huggins to determine the velocities with which stars were approaching or moving away from the Earth. Dunér applied it to determine the rotation of the Sun, by comparing the positions of the lines in the spectrum given by one end of a diameter of the Sun with the opposite end. He chose a part of the spectrum in which there are two dark lines caused by iron in the Sun and also two dark lines caused by the

absorbing influence of oxygen in the Earth's atmosphere. Diagram LXI shows the two spectra. The lines 1 and 3 are atmospheric, and the lines 2 and 4 solar. The former are in the same position whatever part of the Sun the light comes from. The latter are shifted a little towards the violet if they come from a part which by the Sun's rotation is at the moment approaching us, and towards the red end if the light comes from a part of the Sun which is at the moment being carried away from us. The careful measurement of the distances between the lines enables the relative velocities of opposite ends of any diameter to be measured in miles per second. Observations of similar character were made by Dr. Halm at Edinburgh and Mr. Adams at the Mount Wilson Observatory in California. The following table shows the rate at which the Sun is rotating in different solar latitudes—



Diag. LXI.

Lat.	Time of Rotation.
0°	24·5 days
20°	25·5 ,,
40°	27·6 ,,
60°	29·6 ,,
80°	30·6 ,,

The cause of this slowing down as we proceed from the Sun's equator to its poles is difficult to understand. There can be no doubt of its reality, for the results given by spots and by the spectroscope are confirmed by the photographs of faculæ and the spectrographs of flocculi. Spectroscopic determinations by means of

the hydrogen lines do not, however, show these differences in different latitudes. The light in this case probably comes from a higher level, and thus gives the rotation of a different layer of the Sun.

Periodicity of Sun-spots.—In some respects the appearance of spots on the Sun is a very irregular phenomenon. A spot may last for a few days or for several rotations of the Sun. In the latter case it will be visible for 14 days, then disappear owing to the Sun's rotation, then reappear and cross the visible disc of the Sun in 14 days, then disappear again, and so on. The number of spots on the Sun on any particular day is not subject to any easily definable law. But if the average is taken for a fairly long period, say a year, it is seen that the number of spots fluctuates in a fairly regular manner. The same result holds if the fraction of the Sun's area covered with spots is tabulated. The following table from the measures made at Greenwich shows the mean area of spots in millionths of the Sun's visible hemisphere for a number of years—

Year.	Area covered by Spots	Year.	Area covered by Spots.
1889	78	1898	376
1890	97	1899	111
1891	421	1900	75
1892	1214	1901	29
1893	1458	1902	63
1894	1282	1903	339
1895	974	1904	488
1896	543	1905	1191
1897	514	1906	778

The increase in the area of the Sun covered with spots from 1889 to 1893 and the diminution to 1901 is a fair sample of a fairly regular fluctuation which has been traced in records of Sun-spots from the year 1610 to the present time. Roughly speaking, Sun-spots go through a cycle in a period of about 11 years.

As we have seen, spots are seldom found at more than 45° from the Sun's equator. On the other hand, they are rarely close to the equator. Their distances from it generally are between 30° and 10°. When the number of spots is at a minimum, the few there are occur either near the Sun's equator or at a considerable distance from it. As the number of spots increases the distribution changes, the number near the equator becoming less and less, and those at a distance from the equator coming rather nearer to it.

Attempts have been made, without much success, to connect these changes in Sun-spots with the movements of some of the planets. A very remarkable connection has, however, been clearly demonstrated between Sun-spots and magnetic storms on the Earth, and with the extent of the oscillations which magnetic needles go through day by day. When the Sun has many spots magnetic storms are frequent; when the Sun has few spots they are rare. This is as much as can be said with certainty. It does not follow that because there is a large spot on the Sun there will be a magnetic storm. It has been pointed out by Mr. E. W. Maunder that magnetic storms frequently recur after intervals of from 25 to 27 days. This is the

time in which by the Sun's rotation a spot is brought to the same position on the Sun's visible disc again. He is thus led to suppose that streams of electrified particles shot out from the neighbourhood of Sun-spots may reach our atmosphere and start magnetic storms.

Another phenomenon related to Sun-spots is the form of the Sun's corona. The corona has been observed at numerous eclipses, and it is found that the forms of the corona go through a cycle in the same period as the Sun-spots. Two of these forms are illustrated on p. 120, that of 1898 being characteristic of a time when spots are decreasing, and 1901 when they are at a minimum.

Summing up this chapter, we see that the size, mass, density and chemical constitution of the Sun are known. Its temperature is also known approximately, and a reasonable explanation can be given of how its heat is maintained. Its physical constitution presents difficult problems which have not yet been solved. The nature of and relationship between the different layers which different classes of observation show to exist in the Sun are only very partially known. For the present, the law of the Sun's rotation and the periodicity of Sun-spots are observed facts for which no satisfactory explanation has been given.

CHAPTER VII

THE SOLAR SYSTEM

THE solar system comprises all the bodies, great and small, which are clustered around the Sun. They form a small community of their own, too far distant from the fixed stars to be appreciably affected by them, but all dominated by the attraction of the Sun which keeps them revolving in orbits around himself. The system includes the Earth, with its satellite the Moon, the five planets known to the ancients, and the outer planets Uranus and Neptune, with their satellites. Then there is a large number of small planets whose orbits lie between those of Mars and Jupiter. In addition there are periodic comets and meteor-streams, and a certain amount of finer matter whose existence is made apparent by the Zodiacal light.

The largest and most important members of the solar system are the eight planets: Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus, Neptune. The positions of these planets in the sky can be calculated for many centuries backwards or forwards, as their paths and velocities are known with great accuracy. Three remarkable characteristics of them should be noticed—

(1) These eight planets move in nearly the same plane.

(2) The ellipses described by the planets are nearly circular in shape.

(3) The planets all revolve in the same direction.

The mean distances of the planets from the Sun are readily remembered in terms of the Earth's mean distance. They are as follows—

Mercury	·4	Jupiter	5
Venus	·7	Saturn	10
The Earth	1·0	Uranus	20
Mars	1·5	Neptune	30

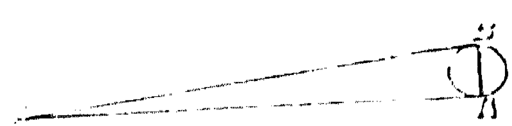
To obtain their periods use Kepler's third law, that the squares of the periodic times are proportional to the cubes of the mean distances. In the case of Neptune, the mean distance $=30$. The cube of 30 is 27,000, and the square root of this is 164. The period is therefore 164 years.

Minor Planets.—Between the orbits of Mars and Jupiter lie the orbits of the minor planets. There are a large number of these bodies, and every year fresh ones are discovered. The first of these small bodies, Ceres, was found by Piazzi on the first day of the nineteenth century. The discoveries of Pallas, Juno and Vesta soon followed. These planets are just large enough to be seen as discs in the most powerful telescopes. The diameter of Ceres, the largest of them, is not far short of 500 miles, and that of Pallas, the smallest, about 100 miles. No more minor

planets were found till 1845, but since that date the numbers discovered annually have steadily increased, especially since photography has been used in the search. The total number at the end of 1900 was 452. Since that date 200 have been added to the list. Most of them are extremely minute. Probably the larger ones have been nearly all discovered. Some of them, particularly Eros, have been of great use in the determination of the Sun's distance; one has served to determine the mass of Jupiter; and several of them illustrate interesting mathematical points in gravitational theory.

It is a striking and interesting fact that these small planets should be confined to this particular region of the solar system; Olbers suggested that they are fragments of a larger planet, but this explanation is very doubtful.

Diameters of the Planets.—The determination of the size of a planet is very simple. As the planet's distance from the Earth is known, it is only necessary to measure the angular diameter seen in the telescope to determine the real diameter. The angle AEB is measured and this value, with the knowledge of the length EA, gives the length AB (Diagram LXII).

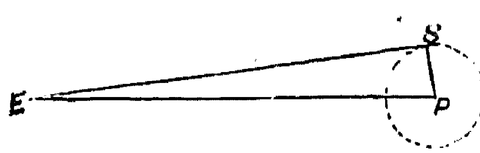


Diag. LXII.

Mercury is the smallest of the major planets, having a diameter of 3000 miles, or $\frac{3}{8}$ that of the Earth; Mars comes next with a diameter about $\frac{1}{2}$, while Venus is

very nearly the same size as the Earth. The other four planets are very much larger; Jupiter's diameter is 11 times, Saturn's 9 times, those of Uranus and Neptune 4 and 5 times that of the Earth.

Masses.—The masses of the planets which have satellites are readily determined from the distances and times of revolution of these satellites. The angular distance of a planet from its satellite is seen and measured in the telescope. Taking the simplest case where a satellite describes a circle about its primary,



Diag. LXIII.

we can, as in Diagram LXIII, measure PES, the greatest angular distance to which the satellite goes from its planet. Knowing the distance EP, the distance PS is found. Let us call this distance a, and let the time the satellite takes to complete its revolution be T. If a is expressed as a decimal of the Earth's distance from the Sun, and T as a decimal of a year, then $\frac{a^3}{T^2}$ will give the mass of the planet as a fraction of the mass of the Sun. This method is applicable to all the planets which have satellites. The masses of Venus and Mercury are more difficult to determine, and are found from the small disturbances they produce on the movements of one another, or of the Earth, or of comets which pass near them. The masses of the planets are generally expressed as fractions of the mass of the Sun. Jupiter, which is by far the largest,

is less than $\frac{1}{1000}$th of the Sun; Saturn comes next, being between a third and a quarter of Jupiter, while Uranus and Neptune are each about $\frac{1}{20}$th. The inner planets are much smaller; the Earth, which is the largest of them, is only $\frac{1}{300,000}$th of the Sun, while Venus is about three-quarters of the Earth, Mars a little more than $\frac{1}{10}$th, and Mercury about a quarter.

Densities.—Knowing the sizes and the masses of the planets, their densities are at once determined. The inner planets do not differ much in this respect from the Earth, whose density is $5\frac{1}{2}$ times that of water. The outer planets are much less dense, Jupiter, Uranus, and Neptune being slightly denser than water, and Saturn not so dense. The differences in density point to great difference in physical state, which arise from the fact that the process of cooling, and its accompanying process of shrinking, have proceeded more rapidly in the small planets than in the large ones.

Rotation.—The planets all rotate about their axes. The definite markings on Mars make its period of rotation easy to determine. It is rather longer than that of the Earth, being 24 h. 37 m. 22·7 s., and is accurately known to $\frac{1}{10}$th of a second. The periods of rotation of Jupiter and Saturn are determinable with fair accuracy, and are both not far from ten hours. Owing to their rapid rotation the figures of these planets are very oblate—so much so that the difference between the equatorial and polar diameters can be seen

in a small telescope. The times of rotation of Uranus and Neptune cannot be given, but they are probably less than twenty-four hours. Owing to the absence of definite markings on Mercury and Venus, their periods of rotation are not known with certainty. The opinion was held for a long time that they rotated in about twenty-four hours, but about twenty-five years ago a very careful examination was made by Schiaparelli, who detected some very faint markings. He concluded that both planets rotate very slowly, so slowly, in fact, that they always present the same face to the Sun. Schiaparelli's results have been confirmed by Lowell. Both these observers have observed the planets assiduously under the most favourable conditions and in the best of climates. Attempts have been made to determine the rotation by spectroscopic observations, but no decisive results have yet been obtained in this way.

Satellites.—The discovery of the satellites belonging to the various planets of the solar system has proceeded from the time of Galileo to the present time. As telescopes have become more powerful, fainter satellites have been discovered. As far as we know, Mercury and Venus have no satellites. The Earth has its one satellite, the Moon, which revolves round its axis in one month, and in consequence always turns the same face to the Earth. Mars has two very small satellites, whose diameters are not more than 6 or 7 miles. They were discovered in 1877 by Asaph Hall

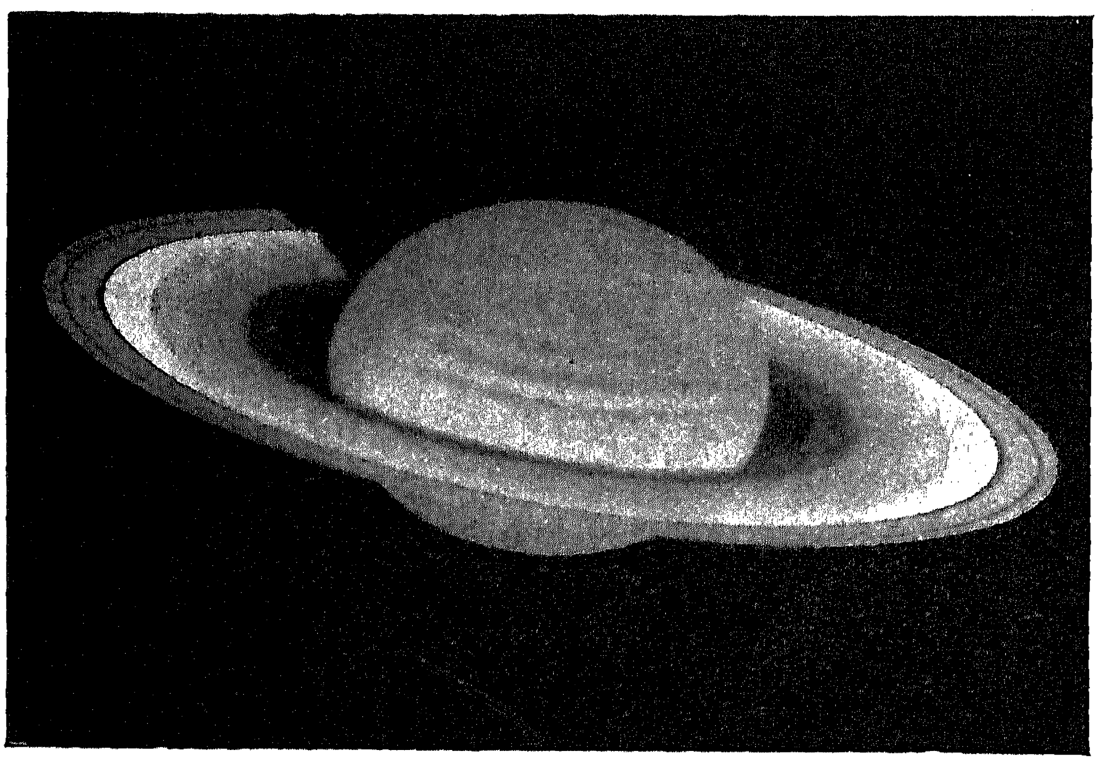
with the large refracting telescope of the Washington Observatory. These satellites, which are named Phobos and Deimos, are very near to Mars, their distances being only 5800 and 14,600 miles respectively, while the diameter of the planet itself is 4200 miles. They necessarily revolve very rapidly, their periods being 7 h. 40 m. and 30 h. 18 m. It is interesting to notice that Mr. Lemuel Gulliver relates that the astronomers of Laputa "have discovered two lesser stars, or satellites, which revolve about Mars, whereof the innermost is distant from the centre of the primary planet exactly three of his diameters, and the outermost five; the former revolves in the space of ten hours, and the latter in twenty-one and a half; so that the squares of their periodical times are very near in the same proportion with the cubes of their distance from the centre of Mars, which evidently shows them to be governed by the same law of gravitation that influences the other heavenly bodies."

The four large satellites of Jupiter were discovered by Galileo in 1610. They can be easily seen with an opera glass, and with a small telescope their transits in front of Jupiter and their eclipses in his shadow can be watched. The smallest is nearly as large as the Moon, and the largest has a diameter nearly half that of the Earth. The nearest is as far from Jupiter as the Moon is from the Earth, and the farthest $4\frac{1}{2}$ times this distance. Their periods round Jupiter are $1\frac{3}{4}$, $3\frac{1}{2}$, $7\frac{1}{4}$ and $16\frac{3}{4}$ days. A fifth and extremely small

satellite was discovered by Mr. Barnard with the great telescope of the Lick Observatory in 1892. This little body is nearer to the planet than the four large satellites, and revolves in 12 hours. It can only be seen with the largest telescopes. In December 1904 a sixth satellite, and in January 1905 a seventh were found photographically by Mr. Perrine at the Lick Observatory. They are very small, and are a long way from Jupiter, revolving in 251 and 265 days. An eighth satellite, still fainter and more distant, was discovered photographically by Mr. Melotte at Greenwich in February 1907. This satellite's distance from Jupiter varies from 10 million to 20 million miles; its period is two years, and its direction of revolution is opposite to that of all the other satellites.

Saturn presents a new feature in its ring. This was a great puzzle to the early astronomers with poor telescopes, who saw Saturn with what seemed like wings, which, moreover, changed their appearance and were sometimes invisible. Huyghens made out clearly in 1655 that Saturn's strange appendage was a luminous ring in the plane of the planet's equator, nowhere touching the planet, and extremely thin. The plane of this ring, like the plane of the Earth's equator, remains always in the same direction, and is inclined at an angle of nearly 27° to the ecliptic. Now, Saturn makes its revolution round the Sun in 29½ years. Like the Earth, Saturn has equinoxes and solstices, and the Sun's position changes from 27°

north to 27° south of its equator. When the Sun is north of the equator, the north side of the ring is illuminated; when south, the south side; while when the Sun is on the equator, only the edge of the ring. The ring is so thin that it is invisible to us when the Sun is in such a direction that it only shines on the ring's edge. Generally the Earth and Sun are both north or both south of the ring, but it may happen, near the time when the Sun passes from north to south, that they are on opposite sides, in which case the ring is also invisible. A division in



Diag. LXIV.—Saturn.

the ring was discovered by Cassini in 1675 separating it into two, and in 1850 it was seen to be continued on its inner rim by a "dusky" ring. The

nature of Saturn's ring was made clear by Clerk Maxwell in 1856. He showed that it could be neither a solid nor a liquid, but must consist of a swarm of little satellites circulating round the planet. If the ring were solid the outer parts would rotate faster than the inner, but if made of separate particles, more slowly. Keeler, at the Lick Observatory in 1895, put this to the test by determining spectroscopically the rates at which different parts of the ring were moving, and thus confirmed experimentally what Maxwell had proved mathematically.

Besides its ring, Saturn has no less than ten satellites. The largest of these, Titan, was discovered by Huyghens in 1655. Its diameter is about 3500 miles. It revolves round Saturn in about 14 days, and is distant about 20 radii of Saturn. Four more satellites were discovered by Cassini between 1671 and 1684. A hundred years later, Sir W. Herschel discovered two smaller ones distant 3 and 4 radii from the planet. An eighth small satellite at a distance somewhat greater than Titan was found independently by Bond and Lassell in 1848. A ninth was discovered in 1899 by Prof. W. H Pickering from photographs taken at Arequipa. This satellite is so distant that it takes one and a half years to complete its revolution. It moves in a retrograde direction in a very elliptic orbit. Still another very small satellite has been found by Mr. Pickering.

Uranus, the planet discovered by Sir William Her-

schel in 1781, has four satellites. Two of these were discovered by Herschel in 1787, and the remaining two by Lassell in 1851. They are remarkable because they move in a plane almost perpendicular to the plane of the motion of Uranus round the Sun.

Neptune has one satellite, discovered by Lassell, which moves in a retrograde direction in a plane inclined at 35° to the plane of Neptune's motion.

It is important to notice that the satellites generally move in planes not far removed from the ecliptic, and revolve around their primaries in the same direction in which these revolve round the Sun. The exceptions are the satellites of Uranus, the satellite of Neptune, and the small and distant ninth satellite of Saturn and the eighth satellite of Jupiter.

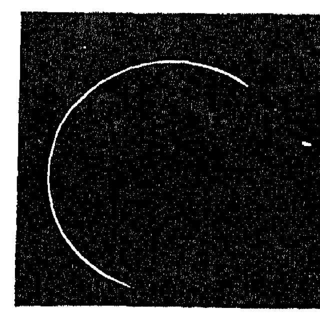
We come now to the consideration of the physical conditions of the planets. What are their temperatures? Are they solid bodies like the Earth? Have they atmospheres?

Temperatures of the Planets.—The four inner planets, Mercury, Venus, the Earth and Mars, receive most of their heat from the Sun. It is possible to form an idea of their temperatures from the consideration that the heat they receive from the Sun just balances the heat which they radiate into space. The uncertain factor in drawing definite conclusions lies in our ignorance of the extent to which the temperatures of planets are regulated by their atmospheres. How greatly an atmosphere affects

temperatures is seen at once from the small average difference between day and night temperature on the Earth. Professor Poynting, who has considered the temperatures of the planets from this point of view, has shown that it is very probable that, whether Mars has an atmosphere like the Earth or is like the Moon and has none, the temperature is everywhere below the freezing point of water. The only escape from this conclusion in his view is that an appreciable amount of heat is issuing from beneath the surface. But we see by comparison of the equatorial with the polar temperatures on the Earth to what an inappreciable extent the internal heat of the Earth modifies its surface temperature. There is thus no reason to suppose that the internal heat of Mars has any considerable effect on its surface temperature. The temperatures of Venus and Mercury, if they revolve round their axes and have atmospheres, are 100° and 300° Fahrenheit respectively hotter than the Earth. If they revolve so as to present the same faces to the Sun always, then the hemispheres which look at the Sun are much hotter than this, and the hemispheres which look away from the Sun are at very low temperatures indeed. When we come to the major planets it would seem that their surface temperatures are determined by the internal heat of the planets themselves, rather than by the radiant heat received from the Sun. Jupiter is probably at something like a red-heat, but it does not emit

sufficient light to illuminate its satellites when they are shaded from the Sun. Saturn, Uranus and Neptune are probably at higher temperatures.

Atmospheres of the Planets.—A bright rim of light, as shown in Diagram LXV, which has been seen round the dark disc of Venus a little before it passed in front of the Sun at the transits of 1874 and 1882 shows that the planet has an atmosphere. It would seem likely that both Venus and Mercury are surrounded by very dense clouds which hide the solid body of the planet. The spectra of Mercury and Venus are very like that of the Sun, and do not suggest that the light, after leaving the Sun, has passed through any absorbing atmosphere besides the Earth's. The explanation may be that the light by which we see these planets is reflected by high clouds, and does not traverse the densest parts of their atmospheres. The question of the atmosphere of Mars is one of great interest as well as one of considerable difficulty. The spectrum of Mars apparently shows no lines which are not in the solar spectrum. The question which has to be decided is, "Are certain lines which we know to be produced by absorption in the Earth's atmosphere more intense than can be accounted for by this terrestrial absorption alone?" To answer the question the spectrum of the Moon, taken as far as possible under the same instrumental and atmospheric conditions, is compared with



Diag. LXV.

that of Mars. Sir W. Huggins and Dr. Vogel considered that the evidence pointed to the existence of water-vapour in the atmosphere of Mars, but Prof. Keeler at Allegheny, and Prof. Campbell at the Lick Observatory, found no appreciable difference between the spectra of Mars and the Moon, and therefore no direct evidence of any atmosphere. Recently Mr. Slipher at the Lowell Observatory has found that a band in the red end of the spectrum, caused by water-vapour, is intensified in the spectrum of Mars. Still more recently Prof. Campbell, observing from the top of Mt. Whitney, the highest mountain in the United States, in order to reduce as far as possible the effect of the Earth's atmosphere, found no difference between the spectra of Mars and the Moon. These observations, made under most favourable conditions, prove that the Martian atmosphere must be extremely rare. In the spectrum of Jupiter there appears to be one line not in that of the Sun, pointing to a constituent of its atmosphere with which we are unacquainted on the Earth. The spectra of Uranus and Neptune show very considerable differences from that of the Sun, from which the inference is drawn that they are surrounded by dense atmospheres totally different from our own.

Mars.—Mars and Jupiter are the only planets which show any considerable detail when carefully observed. Mars shows white caps at the poles which diminish in the Martian summer. If we take the view that Mars has an atmosphere like the Earth, but much less

dense, containing water-vapour, these white caps would naturally be interpreted as snow. The rapidity with which they disappear is sufficient proof that they cannot be thick masses of ice and snow such as we find at the Earth's poles, but a very thin deposit of snow or hoar frost. The drawings by Prof. Barnard, made with the 36-inch reflector of the Lick Observatory, show the melting of the snow (if snow

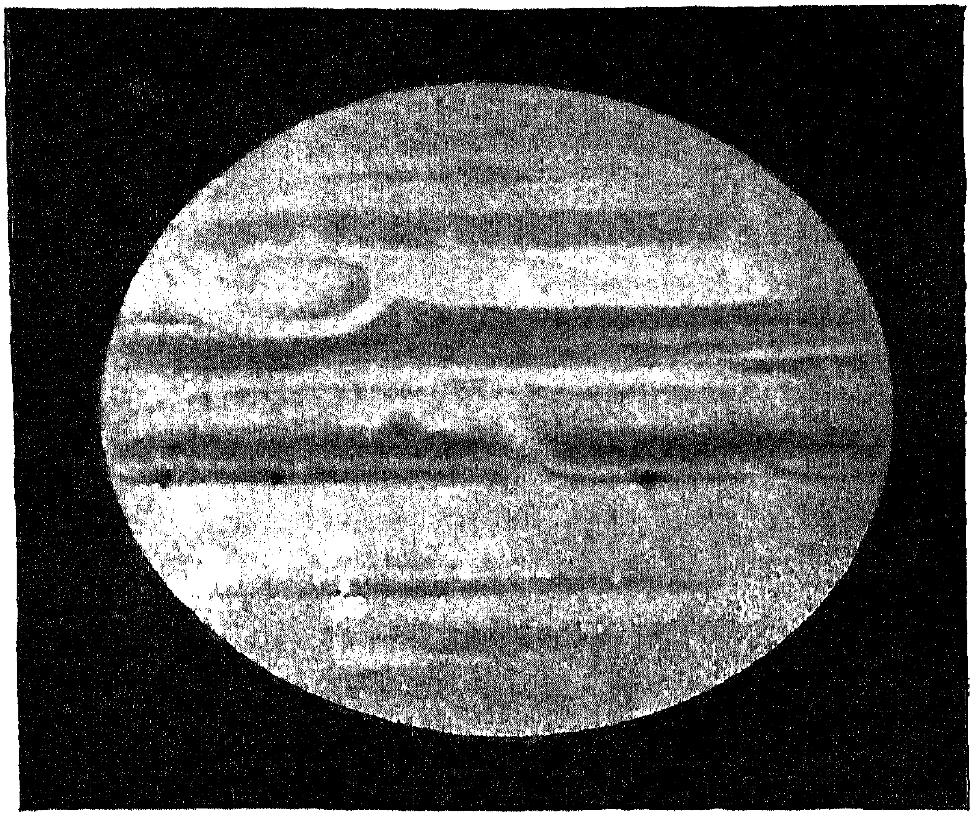
Diag. LXVI.—Mars.

it be) at the south pole of Mars in the year 1894. The features we see in Mars were for a time supposed to be land and seas. We may be pretty confident from the absence of clouds, and the probable low temperature of the planet, that the dark parts are not seas, but solid land of a different colour. A long con-

troversy has raged about the so-called canals, or thin lines, first discovered by Signor Schiaparelli, and since delineated and mapped by Prof. Lowell. The atmospheric conditions of both these observers have given them opportunities which few others possess, and they have devoted a great deal of time and attention to the study of the planet. But, on the other hand, Prof. Barnard at the Lick Observatory failed to see the "canals," although he could see (at moments when the atmospheric conditions were very favourable) a much greater wealth of detail than he could delineate. Prof. Barnard's observations have been confirmed by observers with the largest telescopes in America and Europe. Recently very fine photographs of Mars have been taken at the Mt. Wilson Observatory in California, and do not show the sharp thin lines which have been named "canals." It has been suggested that the canals are really subjective, and arise from the tendency of the eye to join up by lines markings which are only seen with difficulty.

A very small telescope is sufficient to show the belts of Jupiter. Diagram LXVII shows the planet as seen with the 36-inch telescope of the Lick Observatory, and drawn by Prof. Barnard in 1890. The surface of the planet is continually changing. Bright and dark spots appear, last a few months, and disappear. One of the most permanent features is a large red spot which appeared in 1878, and continued without much change of brightness till 1888, when it

became much fainter, but recovered its distinctness in



Diag. LXVII.—Jupiter.

1890, and still more in 1891. It has since grown fainter again, but was just visible in 1907.

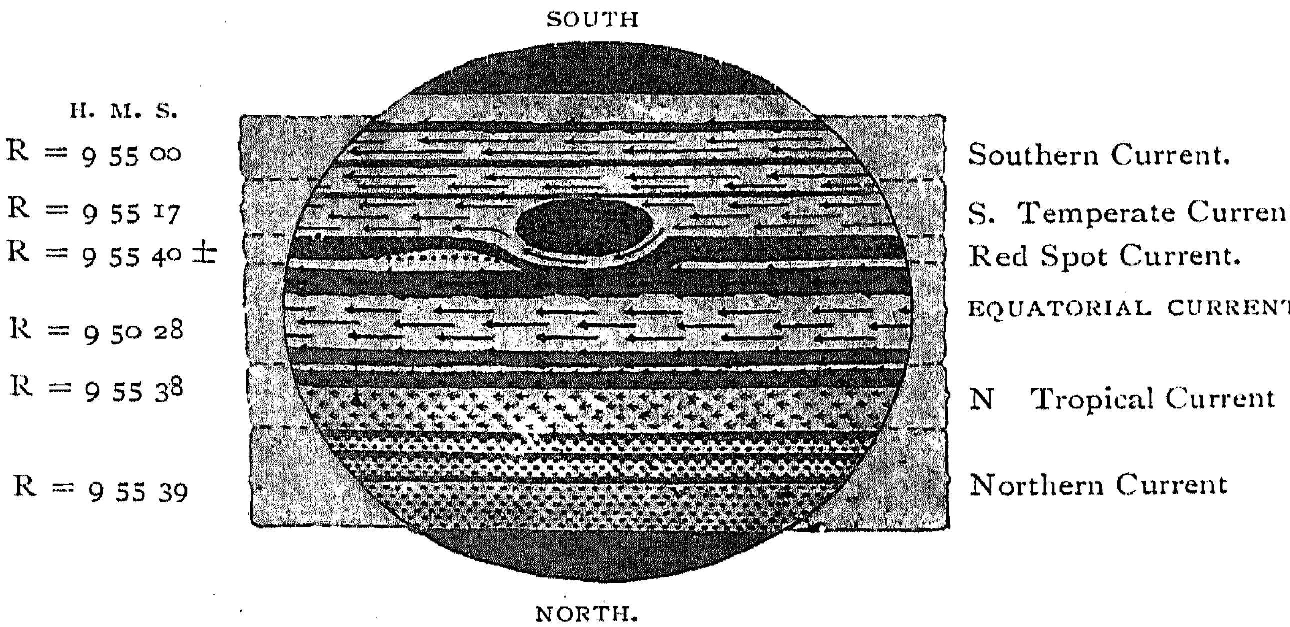
Observations of spots show that the velocity of rotation of Jupiter, like that of the Sun, varies in different latitudes. The following table and diagram is given by Mr. Stanley Williams.

Latitude.	Period of Revolution.	No. of Spots observed.
+ 60° to + 25°	9h 55m 39·43s	9
+ 25° to + 10°	9h 55m 39·92s	15
+ 10° to 0°	9h 50m 23·88s	27
0° to − 12°	9h 50m 27·85s	21
− 16° to − 28°	9h 55m 8·2s	1
− 28° to − 45°	9h 55m 0·9s	2
Red Spot	9h 55m 40·58s	—

L

The large and sudden difference between the velocity of the equatorial current and the currents in the adjacent zones is most remarkable. A difference of 5 m.

SURFACE CURRENTS OF JUPITER IN 1887-8.



Diag. LXVIII.

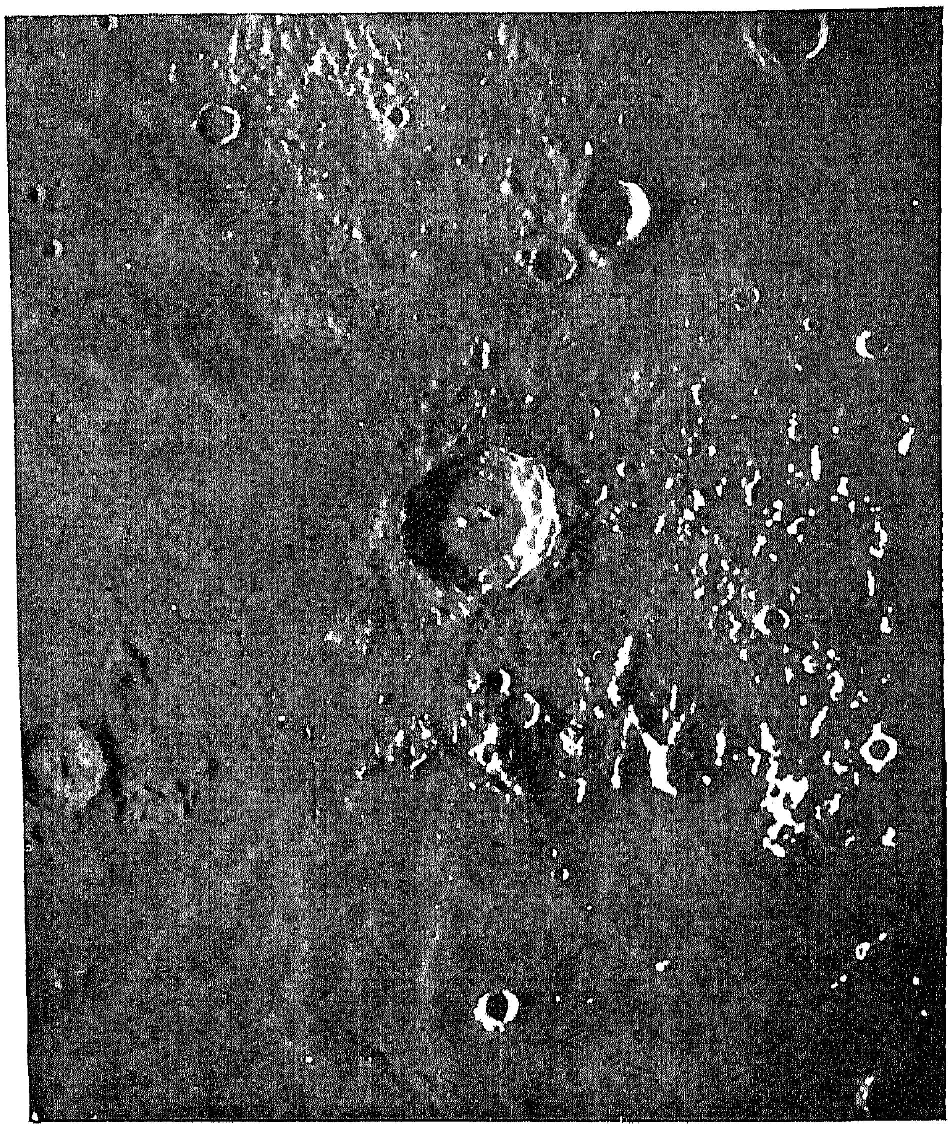
in the time of rotation means a difference of velocity of the adjacent currents of more than 200 miles an hour. Jupiter is clearly not a solid body, and it would be easier to explain this great difference of velocity on the assumption that it is gaseous rather than liquid. But the permanence of the red spot is favourable to the view that Jupiter is liquid. The spot seems to be of the nature of an enormous floating island, the base of which extends down into the denser or more solid regions of the planet.

The Moon.—Our knowledge of the Moon is far more extensive and certain than our knowledge of Jupiter and Mars. It is more than 100 times nearer than Mars,

and with the highest magnification of our telescopes can be seen as it would appear to the naked eye at a distance of about 200 miles. At this distance a circle a mile and a half in diameter would appear as large as the whole Moon does at its distance of 240,000 miles, so that towns, lakes, etc., if they existed on the Moon, could be distinguished. The most conspicuous features on its surface are the craters. Some of these are 50 to 100 miles in diameter, and frequently have a small peak in the centre. They can be well seen with a small telescope. The best time to look at the Moon is when it is nearly half-full; near full-moon the Sun's illumination is too direct to produce shadows, and there is not sufficient contrast for the details of the surface to be seen. Besides the craters, there are mountain ranges and the flat plains which Galileo named seas. The surface of the Moon has been very carefully mapped and studied, and in recent years very beautiful photographs, capable of a large magnification, have been taken, especially at the Observatory at Paris by MM. Loewy and Puiseux. Diagram LXIX shows "Copernicus," one of the most conspicuous of the craters, and is taken from a photograph by Prof. Ritchey.

There is very conclusive evidence that the Moon can have but a very slight atmosphere, not more than one thousandth part of that which the Earth possesses. Moonlight when examined by the spectroscope is found to be a faint copy of sunlight.

No absorption is found such as would occur if the light before reaching us had passed twice through an atmosphere at all comparable with that of the Earth



Diag. LXIX.—Copernicus.

in depth and density. The absence of any refraction when the Moon passes in front of and occults a star is further evidence that it has no atmosphere, or at most an extremely small one. No clouds or hoar frost are seen, and we therefore conclude there is no water. Without air and water one would naturally

suppose few changes to occur on the Moon's surface. With one very doubtful exception, none have been observed.

Comets.—We have seen that Newton showed (a fact afterwards confirmed by Halley in a striking manner) that comets moved round the Sun under the influence of gravitation, and are therefore to be regarded—for the time being, at least—as members of the solar system. The name comet, or "hairy star," was given to those nebulous bodies usually possessing a tail, or tails, which occasionally appear in the sky for a few weeks or months, and then disappear sometimes for ever, and sometimes to be seen again after an interval of years. They move, as Newton found, in highly elliptic orbits, in which case they return to the Sun after an interval of years, or in parabolic or hyperbolic orbits, in which case their velocity is sufficient to carry them beyond the restraint of the Sun's gravitation. Since the invention of the telescope many comets have been found, and usually four or five are discovered every year. These telescopic objects are, as a rule, faint, insignificant, nebulous patches without tails. But every few years one appears which is visible to the naked eye. The total number of such recorded during the Christian era probably exceeds 500. A few of these have had such bright and extensive tails that they have frightened beholders, who regarded them as portents by which

"The heavens themselves blaze forth the death of princes."

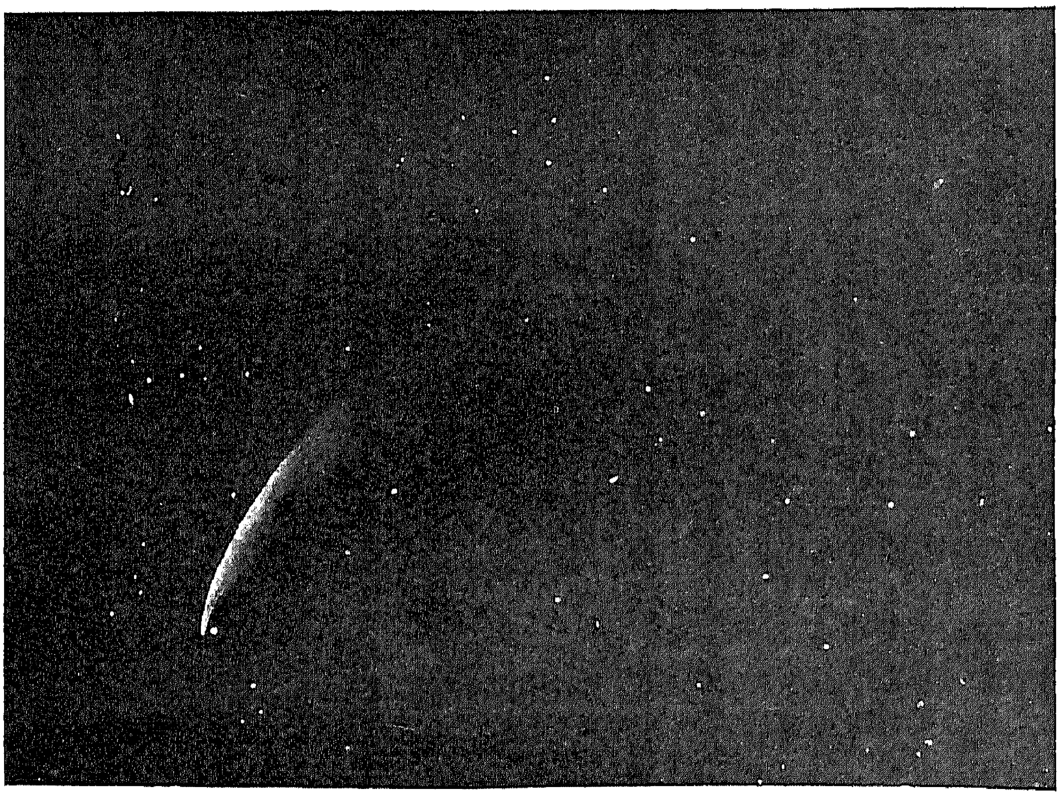
The death of Julius Cæsar and the battle of Hastings among other historical events were believed to have been heralded by comets.

When a comet is examined carefully it is seen that it may be divided into three parts, although these parts run into one another so gradually that it is impossible to say where the exact limits between them are situated. There is first a bright *nucleus*, which is merely a bright point in the telescope just like a star. Surrounding the nucleus is the *coma*, a hazy, cloudy area of light. It is brightest near the nucleus, and gradually grows fainter. The nucleus and coma together constitute the *head* of the comet. Shading away from the head, and growing fainter and fainter till it can be no longer seen, is the *tail*. The tail streams away from the head in a direction opposite to that of the Sun.

The most striking comet of last century was Donati's of 1858. When discovered on June 2 it was faint and without a tail, and it was not till September that its brilliant tail developed. By the middle of October this stretched over nearly a quarter of the sky, being 40° long and about 10° wide in its widest part. The illustration (Diagram LXX) shows its naked eye appearance. This comet may return in about 2000 years.

By far the larger number of comets move in orbits not very different from parabolas, but a considerable fraction have an orbit which is sensibly elliptic. Such comets are periodic, and are seen at each return to

perihelion, or point of the orbit nearest to the Sun. Halley's comet is an instance of this class, and is visible at intervals of 75 years. But some have much shorter periods. The shortest of all is Encke's, with



Diag. LXX.—Donati's Comet, October 1858.

a period of three and a half years. This comet, though a faint one, is of special interest, as a diminution of its period of revolution seems to show that in its course it is impeded by a resistance of some kind, possibly of meteoric or gaseous matter.

Halley's comet and several others have periods of a little over 70 years, and the furthest distance from the Sun to which they reach is beyond the orbit of Neptune. Their orbits are such that these comets have at some time been near to Neptune.

Similarly, Encke's comet, and all those whose periods are less than eight years, move in orbits which at some point are comparatively near to that of Jupiter. The orbits of several others are related in a similar way to the planets Saturn and Uranus. It is clear that these planets have been in some way instrumental in determining the orbits which their respective families of comets describe. Several hypotheses have been put forward to assign more definitely the parts played by the planets. The favourite one, though not free from difficulty, is that the comets which were, so to speak, moving past Jupiter or Neptune, as the case may be, were "captured" by the gravitation of the planet. If a comet at any time in its history passed very near Jupiter, its velocity might be increased or might be retarded. Those whose velocities were sufficiently retarded would move in more restricted orbits.

Comets are only seen when they are comparatively near the Sun. From their high velocities it is inferred that they travel to great distances from the Sun. But we cannot say with certainty that any have been observed to be moving sufficiently fast to get clear away from the solar system. The converse proposition also holds that comets have not been swept into the solar system as it is moving through space, but are bodies which accompany it on that journey.

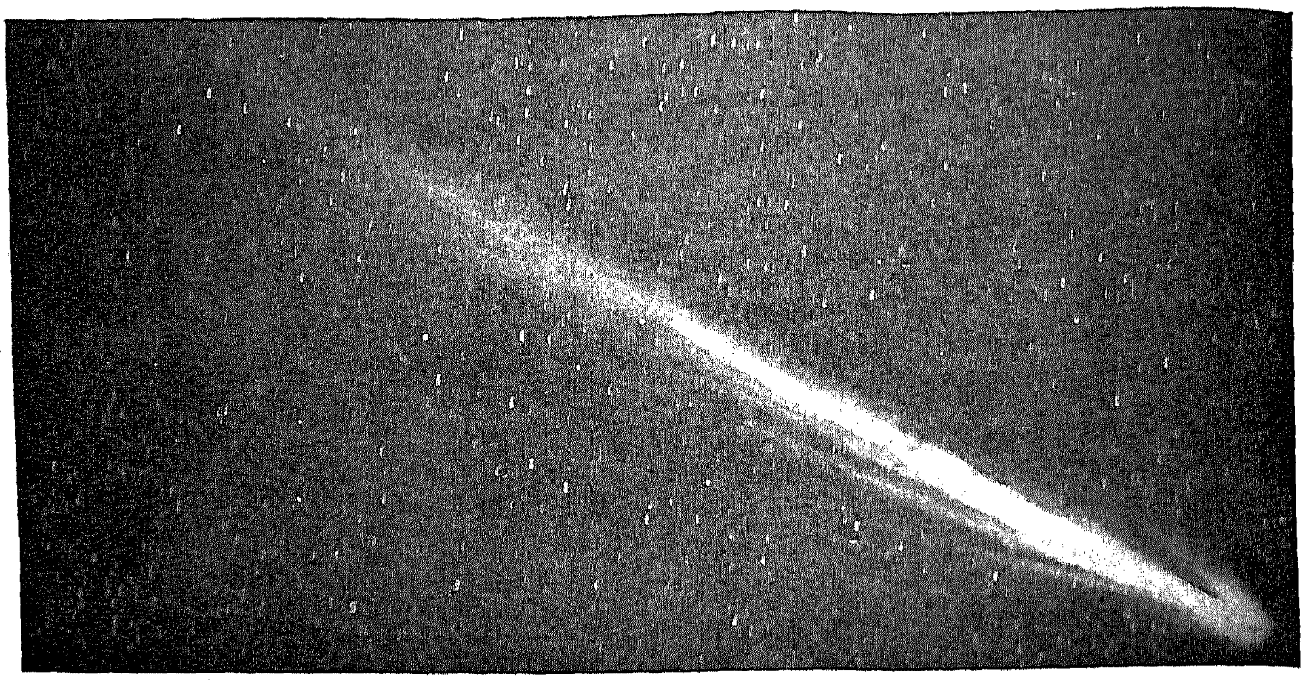
Comets are of great volume but small mass. The head is often more than 100,000 miles in diameter. Nevertheless, no disturbance in the movement of any

of the planets or satellites has been detected in consequence of their proximity to a comet. Several have been near the Earth and had their movement modified appreciably, but yet have made no sensible modification in the movement of the Earth. Thus their masses are small compared with the Earth, probably less than one hundred thousand times. We cannot say how much less, and measured by other standards the mass may be very great. If the mass were one millionth of that of the Earth, it would be the same as that of a globe as dense as the Earth and 80 miles in diameter.

The spectroscope was first applied successfully to determine the constitution of comets by Sir William Huggins in 1868. He found bright bands in the spectrum of the head which indicate the presence of hydrocarbons. These bands have since been found to be characteristic. In addition there is a faint continuous spectrum, and occasionally the dark Fraunhofer lines are seen, showing that a small part of a comet's light is reflected from the Sun. When a comet is very near the Sun, bright metallic lines are sometimes seen in the spectrum of the nucleus, especially those of sodium. We may infer that the nucleus of a comet probably consists of a collection of solid and metallic bodies surrounded by gaseous hydrocarbons.

The formation of the tail is very interesting. At a considerable distance from the Sun a comet is usually a hazy, nebulous object. As it approaches the Sun

it brightens, the nucleus becomes more distinct, and sends out gaseous matter in the direction of the Sun. This is repelled by some force from the Sun, and driven backwards so that a tail or tails are produced on the side of the nucleus away from the Sun.



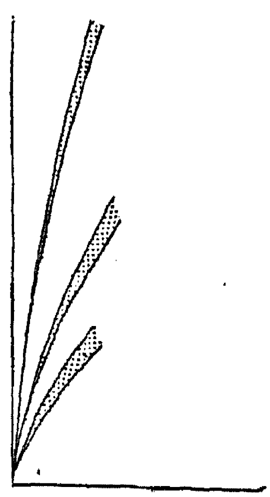
Diag. LXXI.—Morehouse's Comet, 1908.

These tails are not straight, but are curved because the matter driven from the nucleus shares its orbital motion round the Sun. The curvature is shown in the illustration of Donati's comet on p. 151. In recent years very beautiful photographs have been taken which show the details of the tails for a short distance from the head. Diagram LXXI shows a photograph of Comet Morehouse, taken at Harvard. The feature which first strikes the eye in these photographs is one which is irrelevant to the tail of the comet, namely, the short parallel lines which are strewn all over the picture.

They are merely the "trails" of stars which are photographed with the comet. The camera or photographic telescope is kept pointing at the comet during the exposure, but as the comet is moving among the stars, the telescope is moving slightly relatively to them, and they come out on the photograph as short lines. The direction and length of the lines show the direction and amount of the movement of the comet in the sky while the photograph was being exposed. Some comets are seen to have several tails issuing from the head which change from night to night. In Comet Morehouse, of which an extensive series of photographs was made at the Observatories of Greenwich, Yerkes, Heidelberg and others in 1908, it was seen that tails were being constantly shed and new ones produced. Comparison of photographs taken at short intervals of time showed parts of the tail to be moving with large and increasing velocities away from the comet's head.

The movements and changes of a comet's tail are caused by forces in the solar system other than gravitation, and are on this account of great interest. The most detailed theory as yet advanced is due to Bredichin, a Russian astronomer, who concluded that the matter which issues from the nucleus of the comet is driven away by a repulsive force from the Sun. The amount of this repulsive force is not proportional to the mass of the particle of matter, but to the area which is exposed to the Sun. If a small

spherical particle be of the right size, the repulsive force will just balance the attraction of gravitation. For a particle of half this radius, the repulsive force will be one quarter as large, but the attraction only one eighth; for when the radius is halved, the area is one quarter and the volume one eighth as large. The repulsive force is thus most effective for the smallest particles. Bredichin examined the tails of a large number of comets, and found them to be of three types: (i) Long ones showing very slight curvature in a direction away from the Sun; (ii) a plume-like tail curving away more rapidly; and (iii) a short tail curving away very rapidly. The curvature of the tail affords a means of comparing the repulsive forces with the attraction of gravity. Bredichin supposed the long straight tail to be composed of molecules of hydrogen gas; the plume-like tail, which is usually the brightest and most important, to be composed of hydrocarbons; and the short one to consist of metallic vapours (Diagram LXXII).



Diag. LXXII.—Types of Comets' Tails.

We know of two different repulsive forces which the Sun may possibly exert on the matter issuing from the nucleus of a comet. The light radiated from the Sun exerts a pressure on small particles of amount proportional to the surface exposed to it. The difficulty of accepting this as the explanation lies in the fact that the molecules of gases are so very

small that they escape the pressure of radiation. The tails would have to consist of particles one thousandth as small as pin-heads, but very large compared with the sizes of molecules. The immense size and tenuity of a comet's tail favours the hypothesis that it is an extremely attenuated gas, and that the luminosity is to be regarded as a glow produced in this rarefied gas under electrical stimulus. This view has been confirmed by spectra which have recently been obtained of the tails of Daniel's (1907) and Morehouse's (1908) comet. The spectra are made up of bright lines and bands, which prove the tail to consist of glowing gas and not of small solid particles. Spectra which appear to be identical with those of comets' tails have been shown by Prof. Fowler to be given when an electric discharge is passed through vacuum tubes in which certain gaseous compounds of carbon are present, when the vacuum is so high that the pressure is only one 50,000th of that of the atmosphere. Further, one of the lines has been identified by M. Deslandres with the principal line in the kathode spectrum of nitrogen, and the others by Prof. Fowler with the kathode spectrum of a compound of carbon.

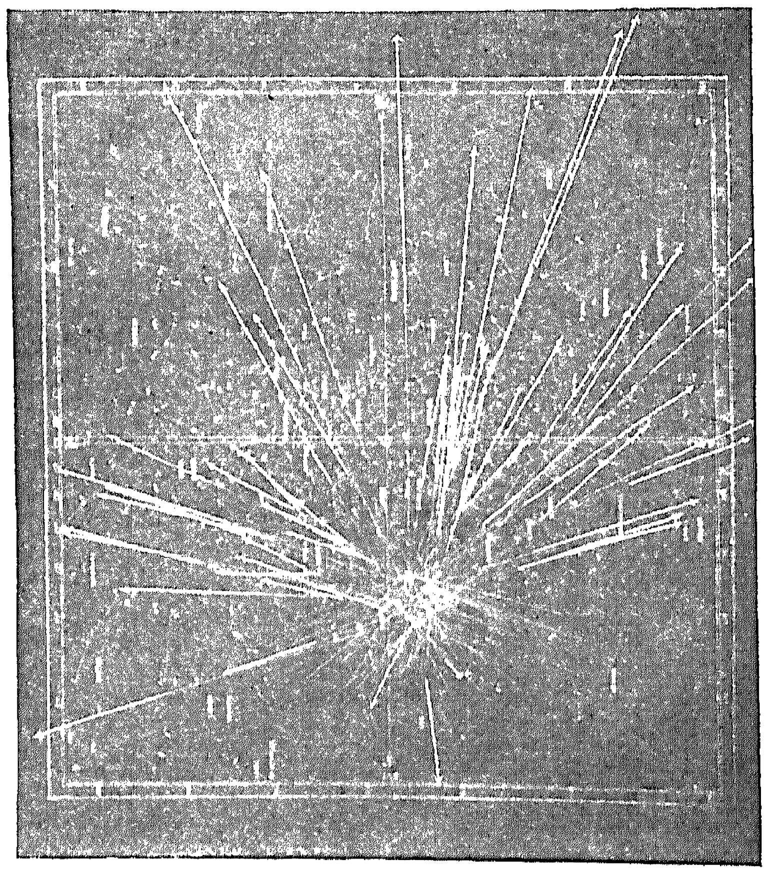
Meteors.—Our views on the physical nature of comets have been derived from the study of meteors almost as much as from that of comets themselves. It becomes necessary to interrupt the account of comets till some of the facts with respect to meteors have been presented. On any bright night a few minutes' watching will be rewarded by the sight of a shooting

star. Sometimes a very bright one is seen by two observers situated in different towns. It is then possible, from the different directions in which the meteor was seen when it burst out and when it disappeared, to calculate its height and path. In this way meteors are found to be at some such height as 80 to 100 miles when they become luminous, and to be at a height of about 10 miles when last seen.

Their luminosity is caused by friction in the Earth's atmosphere, which they enter with velocities which sometimes reach 40 miles a second. A considerable number which have fallen to the Earth have been found. They consist of metallic stones, and contain carbon, iron, nickel and other elements with which we are familiar. Those which fall to the Earth usually weigh a few pounds, while the small shooting stars which are visible almost any night are dissipated into dust while passing through the Earth's atmosphere.

Meteoric Showers.—It sometimes happens that on a particular night a large number of meteors are seen shooting across the sky in all directions. If the paths which they appear to describe as projected against the starry background be drawn on a globe or star map, it will be seen that the paths all *radiate* or diverge from a common point. This point is called the *radiant point*. The existence of a radiant point shows that all the meteors are moving in parallel directions. If, for example, meteors were falling perpendicular to the Earth, their paths when drawn on a

globe would all pass through the zenith. The position of the radiant point gives the direction in which the meteors are moving relatively to the Earth. In Diagram LXXIII the paths of meteors observed at Green-



Diag. LXXIII.

wich on November 13, 1866, are plotted. It will be seen that they all appear to come from nearly the same point of the sky.

The Leonids.—One of the most interesting of these swarms of meteors has its radiant point in the constellation Leo. Meteors diverging from this radiant may be seen on the 13th or 14th of November. The reason they are seen about these dates is that the Earth is then in a part of its orbit where these

meteors are to be met with. The meteors are all moving in nearly the same orbit round the Sun. This orbit and the Earth's intersect at the point where the Earth is situated on November 13 and 14. The key to the question of the cause of the November meteors was found in the recognition of the fact that showers of unusual brilliancy occurred at intervals of about 33 years, or more exactly, three a century. A very brilliant shower was seen in 1833. Records investigated by Prof. Newton of New Haven led him to predict a shower in the year 1866. He concluded that the November meteors were all moving in an orbit round the Sun, but that instead of straggling uniformly about this orbit they were specially thick in one particular part. He found that there were several different orbits which would give rise to a specially brilliant shower about every 33 years. The fact that the date of the shower was gradually getting later, for it was Oct. 19 in A.D. 902, and Oct. 24 in 1202, and Nov. 12 in 1833, enabled Prof. Adams to decide which of these orbits was the true one. In this way it was settled that the November meteors move in an eccentric elliptic orbit which stretches beyond Uranus, and that their period is $33\frac{1}{3}$ years.

Comets and Meteors.—In 1867 it was shown by the researches of Oppolzer and Leverrier that a comet discovered by Tempel in 1865 moves in the same orbit as the November meteors. Schiaparelli showed that the orbit of the Perseid meteors which are seen

in August is probably identical with that of Tuttle's comet of 1862. A third relationship between comets and meteors was shown by the strange behaviour of Biela's comet. This comet was discovered in 1826, and found to have a period approximately six and a half years. In 1846 this comet was seen to split into two, which kept at a distance of about 200,000 miles from each other. In 1852 the two parts were at a distance of two million miles. In 1859 and 1865 the comet was not seen, but in 1872 its place was taken by a shower of meteorites radiating from a point in Andromeda.

We are thus led to regard a comet as made up of a loose collection of meteorites, gathered possibly around a larger central nucleus. When the comet approaches the Sun, heat and other radiative influences tend to disintegrate the mass, and to drive off gaseous constituents. The gaseous constituents thus driven off form the tails.

Nebular Hypothesis. — The Sun, with the planets and comets which circulate round it, forms a system so far from any other celestial bodies that their influence upon it is imperceptible. It pursues its course and undergoes its development entirely apart from them. In a famous hypothesis which he propounded in the *Système du Monde*, Laplace attempted to trace the process of its evolution. He was struck by the facts that the larger planets are nearly in the same plane, that they and their satellites revolve in the same direc-

tion, and that the Sun and planets are rotating in this same sense. These coincidences are too many to be the result of chance, and point to some common cause. He put forward the theory that a vast nebula—diffused tenuous matter—once extended to the confines of the solar system, and under the influence of gravitation slowly contracted. He further supposed that this nebula was endowed originally with a slight rotatory motion. As the contraction proceeded the rotation necessarily increased, and rings or other masses were thrown off which collected and formed planets. This theory received fresh support when it was discovered that heat was developed in the process of contraction. The existence of nebulæ in the sky, and the discovery of their gaseous condition, which we shall come to in a later chapter, was regarded as fresh evidence in its favour. Discoveries made since Laplace's time have shown that there is not quite so much unanimity as he supposed in the directions of planets' rotations and the movements of their satellites. Besides this there are dynamical difficulties, for from the present state of the solar system it is possible to calculate the speed of rotation the nebula had when it extended —let us say—as far as Jupiter, and this speed is not nearly sufficient for any part of the nebula to have been whirled off. The process of evolution cannot be traced by following the simple principle which Laplace enunciated. It has been pointed out recently by Prof. Jeans that "gravitational instability," or a tend-

ency of matter to accumulate around nuclei of slightly greater density, and for these nuclei to increase and gradually collect more and more nebulous matter around them is probably a more important cause than rotation in the development of a planetary system from a nebula. A very careful criticism of Laplace's hypothesis has been given by Messrs. Chamberlin and Moulton. They consider that the solar system has been derived from the aggregation of meteoric dust and fragments, which had possibly resulted from the collision of previously existing bodies.

Sir George Darwin has attempted to trace in detail the birth of the Moon. He supposes that the Earth and Moon were once part of the same fluid body. Owing to its rotation about an axis this body had a spheroidal form. In consequence of the contraction caused by cooling, the speed of rotation increased and the body bulged out more and more at its equator till it reached the limit at which a spheroidal form is possible. As the contraction continued the form changed to an ellipsoid with three unequal axes, then to a pear-shaped figure, and finally split into two bodies. Large tides were generated in these bodies by their mutual gravitation, and the friction of these tides caused the two bodies to separate further. This very complicated question has been mathematically worked out in detail by Prof. Darwin, but there are still some difficulties to be overcome before we can be certain that it is a true account of the Moon's history.

CHAPTER VIII

DISTANCES AND MOVEMENTS OF THE STARS

THE last thing astronomers have learned from the study of the stars has been the nature of the stars themselves. Their vast distances make them appear "fixed" in the firmament, and they have served as reference points from which the movements of other bodies have been inferred and measured. Thus the rotation of the Earth, the movements of the Earth's axis, the velocity of light have all been discovered directly or indirectly by the help of observations of the fixed stars. The fixity of the stars showed the movements of the planets and thus led to the Copernican system. The bright points called planets or wandering stars on the dome of the sky have been shown to be large bodies resembling the Earth which circulate about the Sun. Their sizes, positions and movements have all been determined. The "fixed" stars present a similar but more difficult problem. They appear as bright points projected on the sky. Can they be made to stand out in three dimensions? Can the points on the sky be replaced by material bodies in space whose positions and movements relatively to the Sun are known? Further, can the masses and sizes of the stars be determined?

If the distances of stars were as easy to determine as their directions these questions would be simplified very much. As we have seen, a star's right ascension and declination fixes its direction, just as the longitude and latitude of a place on the Earth fix the direction in which the place would be seen from the Earth's centre. If the distances of the stars from the Earth were known as well as their directions, we should be at once in a position to construct a model of the sidereal universe so far as the positions of the stars are concerned. But the determination of stellar distances is a difficult problem which has lured and baffled astronomers for centuries.

Before we approach this question, it will be convenient to refer briefly to the nomenclature by which stars are identified and to indicate what is meant by the magnitude of a star.

Nomenclature of Stars.—A small number of the brightest stars like Sirius, Arcturus, Aldebaran have been given special names. Next to these come a large number of the stars visible to the naked eye which are named from the constellation to which they belong, being distinguished either by Greek letters or numbers. Bayer in his *Uranometria*, a star atlas published in 1601, used Greek letters, the stars being arranged approximately in order of brightness for each constellation. Thus we have α, β, γ Leonis, etc. Flamsteed, the first English Astronomer Royal, made an accurate catalogue of the stars' positions in which he

designated the stars by numbers as 1, 2, 3 Leonis, etc. The names given by Bayer and Flamsteed have been generally adopted. For fainter stars the number in some well-known catalogue serves as a name. Thus, Br. 3147, Gr. 1830, and Lal. 21185 refer to stars which are respectively No. 3147 in Bradley's catalogue, made in 1755, No. 1830 in Groombridge's catalogue of 1810, and No. 21185 in Lalande's catalogue of 1800.

Positions of Stars in the Sky.—The direction of a star, if it is a bright one, can be obtained roughly from a celestial globe. If the accurate direction is required reference must be made to a star catalogue. The earliest star catalogue in which the positions—that is, the right ascensions and declinations—are given with sufficient accuracy for modern requirements, was made by Bradley from observations at Greenwich about 1755. Since that time the results of many observations with transit circles have been embodied in star catalogues. Throughout the whole of last century, for example, catalogues giving the positions of the brighter stars derived from the most accurate observations were repeatedly made at Greenwich and other national observatories. One of the largest star catalogues, giving the accurate positions for the date 1875 of all northern stars as bright as the ninth magnitude and many fainter ones, was the result of the combined effort of 15 observatories under the auspices of the German Astronomical Society.

Stellar Magnitudes.—The brightness of a star as seen

from the Earth, like its position, is a quantity which admits of immediate measurement. Evidently a knowledge of the stars' distance is required before the *intrinsic* brightness of stars can be compared. If a star's distance were doubled the light received from it would be diminished fourfold, or more generally the light received from equally bright stars varies inversely as the squares of their distances. The quantitative measurement of the light received from stars is a comparatively recent astronomical work, which has been extensively pursued under Prof. Pickering's direction at the observatory at Harvard College, and by Messrs. Müller and Kempf at Potsdam. Various photometric methods have been devised for this purpose, and these have replaced and given precision to the eye-estimations previously made by astronomers. The brightness of a star is indicated by its magnitude, and the photometric scale is such that a difference of one magnitude between two stars corresponds to 2·5 times the amount of light. Thus from a star of mag. 1·0, 2·5 times as much light is received as from a star of mag. 2·0; while from a star of mag. 2·0, 2·5 times as much light is received as from a star of mag. 3·0, and so on. Thus the brightness or amount of light received from a star is related to its magnitude by a formula—

Amount of light $= C \times (\frac{1}{2 \cdot 5})^m$, where m is the star's magnitude, and C is the amount of light received from a star of magnitude 0·0, *i. e.* a star slightly brighter than Vega.

Aldebaran is of magnitude 1·1, or slightly fainter than the first, while Altair is of magnitude 0·9, or slightly brighter. The stars brighter than first magnitude are—

	Mag.		Mag.
Sirius	−1·4	Rigel	0·3
Canopus	−1·0	Procyon	0·5
Vega	0·1	Achenar	0·5
α Centauri	0·2	β Centauri	0·8
Capella	0·2	Altair	0·9
Arcturus	0·3		

Thus Vega gives nearly 2·5 times the light of a first magnitude star, and Sirius gives $(2·5)^{1·5}$, or 4 times the light of Vega.

With the naked eye stars slightly fainter than 6·0 mag. can be seen. A very small telescope will show stars down to 9·0 mag., and with the largest telescopes the sixteenth magnitude can be reached. A convenient rule which connects the brightness of a star with its magnitude is that a difference of 5 magnitudes corresponds to a ratio of 100 : 1 in the amount of light received.

Thus from a star of 1·0 mag. 100 times as much light is received as from a star of 6·0 mag.; from one of 6·0 mag. 100 times as much as from one of 11·0 mag., and from one of 11·0 mag. 100 times as much as from one of 16·0 mag. Thus one millionth of the light of a first magnitude star is received from one of the 16th magnitude.

Number of Stars.—A very interesting question naturally arises as to the number of stars of each magnitude,

About 1855 Argelander at Bonn made a very complete list of all the stars as bright or brighter than 9·5 mag. between the north pole and 2° south of the equator. He enumerated altogether 324,000 stars. This work was continued as far as 23° south declination by Schönfeld, who enumerated in this part of the sky 134,000 stars. From 22° south declination to 52° south declination an enumeration of all stars down to 10·0 mag. made at Cordoba contains 490,000 stars. At the Cape Observatory similar work has been accomplished photographically extending from 19° south declination to the south pole, giving approximate positions and magnitudes of 455,000 stars. The difficulty in researches of this class is in keeping a constant scale of magnitudes, as the magnitudes are necessarily determined by eye-estimation in visual observations, and by what amounts to a very similar process in photographic observations. When corrections are made so that the estimates may be as far as possible according to the photometric scale, the following results are found for the total number of stars of different magnitudes.

Mag.	No. of Stars.	Mag.	No. of Stars.
> 1·0	11	6·0 – 7·0	10,275
1·0 – 2·0	28	7·0 – 8·0	31,000
2·0 – 3·0	105	8·0 – 9·0	93,000
3·0 – 4·0	300	9·0 – 10·0	271,000
4·0 – 5·0	1016	10·0 – 11·0	710,000
5·0 – 6·0	3265		

Our knowledge of the immense number of very

faint stars begins with the Herschels who counted the stars in sample areas in different parts of the sky. The limiting magnitude to which Sir J. Herschel went was approximately 14·0 m. The estimated number of stars down to this limit is nearly 24 millions. With some of the modern reflecting telescopes stars three or four magnitudes fainter than 14·0 mag. can be photographed, and the total number down to 18·0 mag. may be estimated at about 1000 millions.

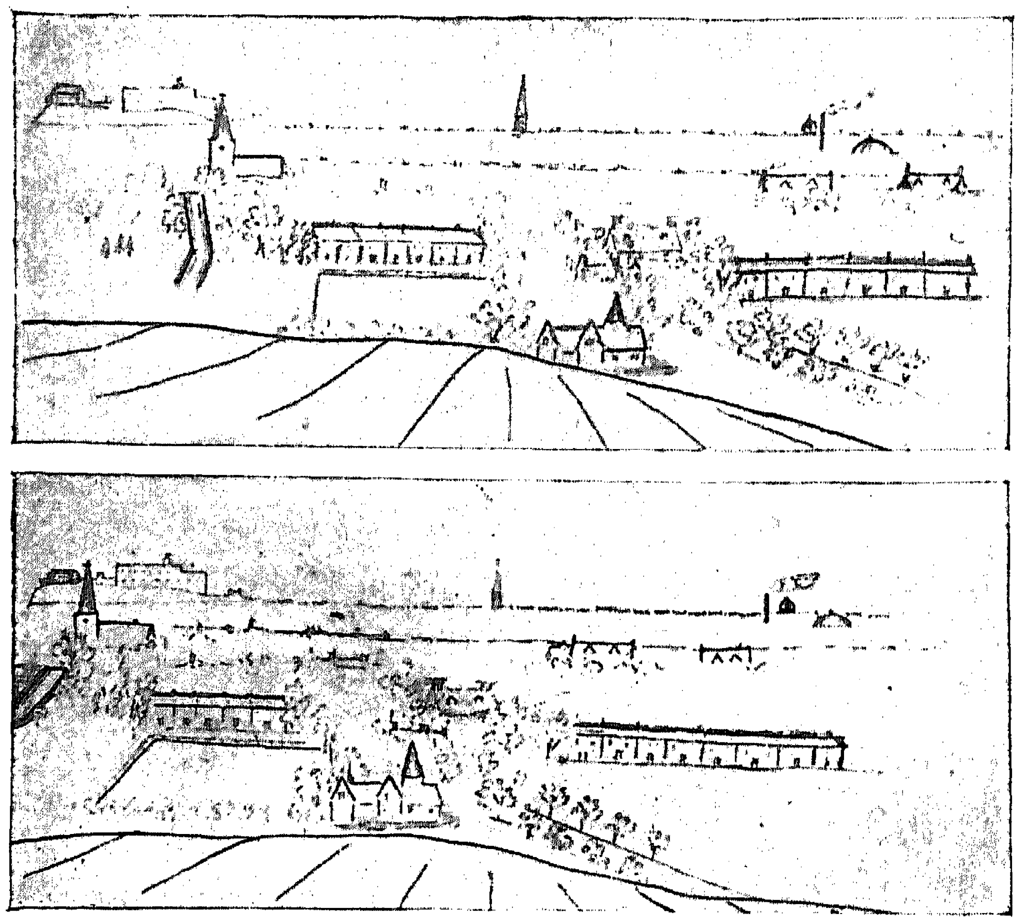
The increase of the number of stars per magnitude is very interesting. It is seen to be roughly 3 times. Now, as the amount of light received from a star is $\frac{1}{2\cdot5}$ times as much as that received from a star a magnitude brighter, it follows that as far as 11·0 mag. the total light contributed by all the stars of any one magnitude is greater than that contributed by the class a magnitude brighter. This cannot go on indefinitely, or the total amount of light received from the stars would be infinite. The ratio of the number of stars per magnitude to the number a magnitude brighter does not appear to fall off very fast for several magnitudes fainter than 11·0 m.

Distance of Stars.—We have seen how the distance of the Moon may be determined by observing the difference of its direction from two points on the Earth's surface; and how the same method carried out with greater refinement enables the distance of Mars and of certain minor planets when nearest the Earth to be measured, and the scale of the planetary system to be derived.

But the distance of the stars is so vast that the most refined instruments show no trace of any differences in their directions as viewed from the north of Europe or South Africa. Such a base-line for their triangulation is absolutely inadequate. When Copernicus showed that the Earth revolved round the Sun, astronomers realized at once that they could use a very much larger base-line. After an interval of six months the Earth has moved from a position 90 million miles on one side of the Sun to one 90 million miles on the other. With such a large base-line as 180 million miles some differences in the directions of the stars which would permit of the determination of their distances was surely to be anticipated. Diagram LXXIV, which consists of rough sketches of Edinburgh from two different points in the grounds of the Royal Observatory, shows the change produced by a slight difference of point of view. The church spire on the left, which is only half as distant as the Castle, is in one sketch seen projected against the right edge of the Castle, but in the other near the middle of it. The chimney on the right, which is a little nearer to the observatory than the crown-like spire of St. Giles' Church, appears in one sketch to the right and in the other to the left of this spire.

But the contemporaries and successors of Copernicus could not find the slightest trace of any parallactic effect of this kind among the stars. Some concluded that Copernicus was wrong, others that the distances of the stars were so great that the distance

of the Sun was inappreciable in comparison with them. As means of measuring angular positions were improved, attempts were renewed to find some



Diag. LXXIV.

small differences in the relative positions of the stars which would show that though very large the distances were not immeasurably great. Of these unsuccessful attempts the most notable are Bradley's, from 1729 to 1748, which led to the discovery of the aberration of light and of a small oscillatory movement of the Earth's axis called Nutation, and Sir William Herschel's, which led to the discovery of double stars

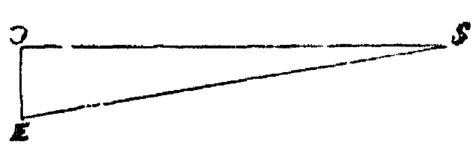
revolving about one another under the influence of their mutual gravitation.

Before the distance of any star was actually measured indications were found that some of the stars though at great were still at appreciable distances. Halley found that the three bright stars, Sirius, Arcturus and Aldebaran, were placed in Ptolemy's catalogue in positions slightly to the north of those they occupied in his own time. He guarded against this being due to errors of Ptolemy's catalogue by observing that the positions of other and fainter stars agreed with those assigned to them by modern observations. In a communication to the Royal Society in 1718 Halley remarks, "These stars, being the most conspicuous in heaven, are in all probability nearest to the Earth; and if they *have* any particular motions of their own it is most likely to be perceived in them, which in so long a period as 1800 years may show itself by an alteration of their places, though it be utterly imperceptible in the space of a single century of years." Halley's conclusions were confirmed by other astronomers, and in 1756 Mayer, a German astronomer, gave a list of 57 stars whose positions had changed perceptibly in half a century due to the movement of the stars themselves relatively to the solar system. At the middle of the eighteenth century it was fully realized that the Sun and stars were similar bodies, but that the stars were vastly more distant. The discovery of movements among them showed that,

though great, their distances were not infinite, and held out hopes to astronomers that with more refined measures these distances might be determined.

Success in measuring the distance of a star was attained almost simultaneously by three astronomers, Bessel, Struve and Henderson. Bessel chose 61 Cygni, a star of only the 5th magnitude, on account of the rapidity of its motion across the sky. Near to this star were two others which did not share this large motion, and were presumably at a much greater distance. He commenced a series of measures with a heliometer in August 1837 and continued them till October 1838. He found a very small movement of the star with reference to both the small comparison stars, analogous to the change in position shown in the diagram of p. 172, arising from the fact that his point of view was changed by the motion of the Earth around the Sun. He concluded that the "parallax" of 61 Cygni was 0·32″.

The parallax is the small angle which the radius of the Earth's orbit subtends at the star's distance.



Diag. LXXV.

If E (Diagram LXXV) be the position of the Earth, $\odot$ of the Sun, and the line $\odot$S is drawn perpendicular to E$\odot$ and carried till $\odot$S represents the star's distance on the same scale, then the small angle ES$\odot$ is called the star's parallax. If S$\odot$ is 200,000 times E$\odot$, then the angle ES$\odot$ will be 1″. Bessel found the angle to be 0·32″

in the case of 61 Cygni, and therefore 61 Cygni is $\frac{1}{0.32} \times 200,000$ times, or more than 600,000 times the distance of the Sun.

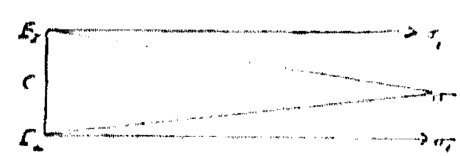
Meanwhile Struve at Pulkova had from 1835 to 1838 been making a similar series of observations on the bright star Vega. This star, though not moving so fast as 61 Cygni, indicates, both by its movement and its brightness, that it is probably one of the stars nearest to the Sun. Struve found for this star a parallax of 0·26″, indicating a distance of 800,000 times that of the Sun. Later observations have shown that the parallax is not so large as this, but nearer to 0·10″, so that its distance is two million times that of the Sun.

Henderson's observations were made by a different method. Appointed H.M. Astronomer at the Cape of Good Hope in 1831, he made a series of observations to determine the declination of the bright double star *α* Centauri. This star, which is the fourth brightest in the heavens, only Sirius, Canopus and Vega being brighter, has a very large proper motion. Henderson examined his observations and found that they showed the star to have a parallax of 1″. His calculations were not made till he had left the Cape on his appointment as Astronomer Royal for Scotland, and he did not announce the result till it had been confirmed by observations of the right ascension of the same star. He published his determination of the parallax of *α* Centauri two months after Bessel had

published that of 61 Cygni. Later and more accurate observations have shown that the parallax is not quite so large but only 0·75″. Nevertheless this star is, as far as we know, our nearest neighbour among the stars, its distance being 270,000 times that of the Sun.

The work of determining the parallax of a star is extremely delicate and very laborious owing to the care which needs to be taken to obtain the necessary accuracy. In recent times the parallaxes of a number of southern stars have been carefully determined by Sir David Gill at the Cape. Among other stars he finds that Sirius has a parallax of 0·37″, but that Canopus is too far away to show any sensible parallax. The star with the largest parallax next to α Centauri is a faint star of magnitude 7·6, situated in the Great Bear. The parallax of this star is 0·46″. There are about twenty stars whose parallaxes are known to be greater than 0·20″, *i. e.* whose distances are less than one million times that of the Sun. On the other hand, even some of the brightest stars, such as Canopus and Rigel, are at such a great distance that they show no certain parallax. The fact that some faint stars are comparatively near, while some bright ones are too far away for their distances to be measured with certainty, shows that there is very great diversity in the actual luminosity of the stars. If all were at the same distance some would appear thousands of times brighter than others.

It is not easy to form any conception of the great distances the stars are from us. If the distance between the Sun and Earth were represented by the distance between two railway lines, the distance of *α* Centauri, our nearest neighbour among the stars, would be 245 miles, and the distance of Sirius would be 500 miles. Thus if two railway lines starting from London instead of keeping parallel at a distance of 4 feet 8½ inches, converged so gradually that they met at Durham, the long triangle thus formed would be similar to that formed by the Sun, the Earth, and *α* Centauri. For more distant stars the triangle would be proportionately longer. The measurement of stellar distances rests on the determination of the small angle at the vertex of the triangle, and as this angle is extremely small the utmost care is necessary to avoid any error due to instrumental causes. For this reason the differential method of determining stellar parallaxes has generally been used; that is, a small change in the position of a star relative to neighbouring stars has been looked for. In Diagram LXXVI if E_1 and E_2 are the positions of the Earth when on opposite sides of the Sun (marked ⊙ in the diagram), and if σ is a comparatively near star and σ_1 a distant one, then $E_1\sigma_1$ and $E_2\sigma_1$ are sensibly parallel, and the angle $E_1\sigma E_2$, which is twice the parallax of the star σ, is the sum of the two small angles



Diag. LXXVI.

$\sigma E_1 \sigma_1$ and $\sigma E_2 \sigma_1$. It is easier to determine the angle $E_1 \sigma E_2$ accurately in this way than in any other, as the many causes except parallax which affect the position in the sky of σ as seen from E_1 and six months later from E_2, equally affect the position of σ_1, but not the relative positions of the two stars.

Unless the stars of reference are much more distant than the star whose parallax is sought, the differential method will fail, but if they are 10 or 20 times as far off the result will be $\frac{1}{10}$th or $\frac{1}{20}$th part too small.

The stars whose distances have been satisfactorily determined number from 150 to 200. Those whose distances have been investigated are in nearly all cases very bright or with very large proper motions. The brightness and the proper motion have been clues which have guided astronomers in the choice of stars whose distances they should attempt to determine. This manner of selection makes it difficult to deduce from the results correct views as to the average distances of stars. Prof. Kapteyn, realizing the importance of an increase in our knowledge of the parallaxes of stars, has set on foot a scheme by which certain selected areas well distributed over the sky shall be photographed at such times of the year that any stars of large parallax will be detected by their slight movements relative to the general mass of the stars photographed on the same plate. When stars of large parallax—let us say greater than 0·1″—are picked out in this way, a great deal

of information will be obtained on many important points on which our knowledge is at present very scanty. For example, the percentage of stars of different magnitudes, having parallaxes of this amount, will show to what extent the apparent brightness of a star is due to its intrinsic brightness, and to what extent it is due to nearness to the Earth. Similarly we shall be able to judge to what extent a large proper motion is due to a large velocity, and to what extent it arises from the star's proximity to the Earth. These and other questions bearing on the geometry of the stellar system depend largely for their answer on the increase of our knowledge of the parallaxes of stars.

Proper Motions of Stars.—Although only a small fraction of the stars are sufficiently near for their distances to be separately determined, there are a large number of stars sufficiently near for their proper motions or angular motion on the face of the sky to be determinable. With the lapse of time the number will increase, for if motion cannot be detected in one year it may be in ten, if not in ten a century may be sufficient. The existence of a proper motion clearly shows that a star is not at an infinite distance, otherwise its velocity would need to be infinite for any change in its position to be produced.

The magnitude of the proper motion does not enable a star's distance to be determined unless the actual velocity of the star is known. The study of

proper motions does, however, give information about the average distances and movements of stars which are too far distant for their parallaxes to be determined individually.

The proper motions of many stars have become known during the last quarter of a century because a sufficient interval of time has elapsed since the positions of the stars were accurately catalogued for changes in their position to be apparent. Modern determinations of proper motion date from the revision by Dr. Auwers of the catalogue executed by Bradley at Greenwich in 1755 and its comparison with catalogues made a hundred years later. By this work the angular movements on the face of the sky of more than 3000 stars were made known. The proper motions of thousands of stars have since been investigated by different astronomers. As examples of the actual amount of stellar proper motions we may take the very bright stars given on p. 168. The number of seconds they move over the face of the sky per century are as follows—

Sirius	132″	Capella	44″	Achenar	9″
Canopus	2″	Arcturus	228″	β Centauri	4″
Vega	35″	Rigel	0″	Altair	65″
α Centauri	368″	Procyon	125″		

Canopus and Rigel show practically no movement, and are probably at a very great distance. As we have seen, attempts to determine their parallaxes have been

unsuccessful. It follows that their actual luminosity must be immense. On the other hand, Arcturus is an instance of a star moving with a very great velocity. Its parallax has been determined as 0·03″. While this is the small angle the distance from the Earth to the Sun subtends at Arcturus, its movement in a year on the face of the sky subtends an angle 2·28″. In one year, therefore, it moves $\frac{2\cdot28}{0\cdot03}$ times the distance from the Earth to the Sun. This works out to be 76×93 million miles a year or more than 200 miles a second.

Large proper motions are not confined to bright stars. Till a few years ago Gr. 1830, a star of 6·9 mag. was the most rapid known; but in 1897 a faint southern star of 8·5 mag. was found to be moving still more rapidly. The following five stars have proper motions greater than 500″ a century.

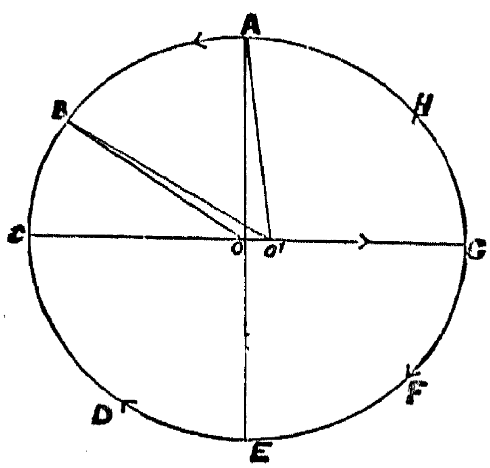
	Mag.	Prop. Motion.	Parallax.
Cordoba V, 243	8·5	870′	0·31″
Gr. 1830	6·9	704″	0·12″
Lac. 9352	7·5	694″	0·28″
Cor. 32416	8·5	607″	——
61 Cygni	5·7	520″	0·33″

The parallaxes show that four of these five stars are comparatively near. The faintness of the stars is therefore a proof of their small absolute luminosity, and illustrates the great variations among the stars in this respect.

Altogether about 100 stars are known to have proper motions of more than 100″ a century, and about 2000

of more than 20″ a century, but the latter list is very incomplete. The probable number of those which have proper motions greater than 5″ a century is given by Newcomb as 20,000, but the data are as yet insufficient for a precise estimate.

Motion of Sun in Space.—The proper motion of a star may arise from its own motion or from a motion of the solar system in space. In the former case there is, *à priori,* no reason to expect any regularity among the proper motions; but in the latter case there would be a general drift of the stars in an opposite direction to the movement of the solar system. In Diagram LXXVII let O be the centre of a large circle, and let O move a small fraction of the radius to O′ in the direction OG. The direction in which A is seen has changed from OA to O′A; A has apparently moved in the direction of the arrow through an angle COA—CO′A or OAO′. Similarly E has apparently moved through an equal angle. G and C, which are in the direction of and the direction opposite to the movement of O, have not changed their directions at all. A point B has apparently moved through an angle COB—CO′B or OBO′. This angle is largest when B is like A or E, perpendicular to OO′, and becomes smaller as B approaches C, the point from



Diag. LXXVII.

which O is moving or the point G to which O is moving. If, instead of dealing with a circle, we take a sphere like the sky, the apparent angular movement of the stars arising from the real movement of the Sun (carrying the Earth with it) will be towards the point from which the Sun is moving. The movement will be imperceptible in stars near this point or 180° away from it, and will be largest for those 90° distant. There are two complications when this geometrical conception is applied to the stars. First, part of a star's proper motion arises from the star itself; and secondly, the unknown and irregular distances of the stars prevent the effect from being as regular as in the geometrical illustration just given. One of Sir William Herschel's greatest discoveries was his perception of a certain amount of regularity in the proper motions of stars, and his attribution of this to a translation of the solar system in space towards a point in the sky which he fixed in the constellation Hercules near the star λ Herculis.

Herschel's first determination of the direction of the solar motion was made in 1783. He obtained from very little material a result in very good agreement with modern determinations. He made a new determination in 1805, and found for the Sun's apex or point towards which the Sun is moving a position 30° distant from λ Herculis. This discordance led some astronomers, and among others Bessel, to doubt

whether a movement of the solar system had really been established.

In 1830 Argelander made very exact observations of a number of bright stars. He compared the positions of 390 of these with those found by Bradley in 1755. The interval of 75 years between the observations provided him with a very considerable change of base—the distance through which the solar system had moved in 75 years. His research, which was carried out with considerable mathematical refinement, confirmed Herschel's earlier result. Many determinations of the solar motion have been made in comparatively recent years. The comparison of modern observations with the older ones of Bradley and others have given the proper motions of a large number of stars, so that bright stars and faint stars, stars of large and of small proper motions have been used in different determinations. Further, the difficulties and uncertainties of the problem have given rise to the development of somewhat different mathematical methods of treatment. The results were not as accordant as might have been anticipated, and in searching for the cause of the discrepancies Professor Kapteyn discovered an interesting feature in the proper motions arising from peculiarities in the motions of the stars themselves. The different methods by which the problem had been treated assumed that, apart from the apparent movements arising from the real movement of the solar system

in space, the movements of the stars themselves were haphazard. It has been clearly demonstrated that this is not the case, but that the stars' movements exhibit a bias towards a direction whose right ascension is about 90° and declination about $+15^\circ$ and the direction diametrically opposite. The point in the sky towards which the solar system is moving has right ascension 275° and declination $+30^\circ$, and is not far from the bright star Vega. It is to be understood that there is an uncertainty of several degrees in the positions determined for both of these points.

Motion in the Line of Sight.—The information derivable from the proper motions of stars has in recent years been supplemented by determinations of the actual velocities with which stars are moving to or from the Earth. The application of the spectroscope for this purpose was first made by Sir William Huggins in 1868. The position of a line in the spectrum is determined by the number of vibrations which are received each second. If the source of light is approaching the observer, more vibrations are received per second than is the normal case when the source of light is at rest. Suppose the spectrum contains known lines, for instance, those due to Iron. These will all be displaced slightly to the violet side of their positions in the normal spectrum of Iron; and the amount of the displacement affords a means of comparing the velocity of the source of light towards the observer with the velocity of light. If the source of light is receding

from the observer the lines are displaced towards the red.

The initial difficulties of applying this principle to determine the velocities of the stars to or from the Earth were very considerable owing to the small amount of light from a star and also on account of the minuteness of the displacement. Sir William Huggins showed that the method was feasible, and Dr. Vogel, by substituting photographic for visual observations, substantially increased its accuracy. Later with the large telescope of the Lick Observatory, Prof. Campbell obtained still higher accuracy, and at the present time there are half-a-dozen observatories where the velocity of a bright star to or from the Earth can be obtained with a probable error of not more than half-a-mile a second. It is to be noted that, provided there is enough light for an observation to be made, the information we derive of the stars' velocities in this way is irrespective of their distance. As might be expected the velocities with which the stars are approaching or receding from the Earth vary considerably. Those with the greatest velocity determined at the Lick Observatory are—

η Cephei	55	miles	per second	towards	Sun
ζ Herculis	45	,,	,,	,,	,,
ϵ Andromedae	53	,,	,,	,,	,,
μ Cassiopeiae	61	,,	,,	,,	,,
δ Leporis	59	,,	,,	from	Sun
θ Canis Majoris	59	,,	,,	,,	,,

From the velocities of 280 stars Prof. Campbell determined the direction and amount of the solar motion. The method is essentially the same as that employed in the case of proper motions. The velocity found for each star is supposed to be compounded of the velocity of the solar system and of the star itself, and from the manner in which stars at one part of the sky are systematically found to be moving towards the Sun, and in a diametrically opposite part of the sky to be moving from the Sun, the velocity with which the solar system is moving through space is found to be about 12½ miles per second.

Average Distances of Stars.—This velocity of 12½ miles per second in a year carries the solar system forward a distance equal to $4a$ where a is the distance of the Earth from the Sun. In 100 years, therefore, the solar system moves a distance $400a$, and the stars are seen from points 200 times as far apart as the extreme distance which the revolution of the Earth about the Sun supplies.

Referring to the figure on p. 182, we may take O to be the position of the Sun in 1800 and O′ in 1900. Let us suppose a number of stars at equal but unknown distances from the solar system to have had their positions in the sky observed in 1800 and again in 1900. From comparison of these observations the angle OAO′ may be determined, and then as the length OO′ is known, the distance OA of these stars

can be found. As the stars are not all at the same distance, the application of this method in practice only gives the average distance of the stars considered. As an illustration, take the stars observed by Groombridge in 1810 and re-observed at Greenwich about 1890. There were 200 stars brighter than 5·0 mag., 454 between mags. 5·0 and 6·0, 1003 between mags. 6·0 and 7·0, 1239 between mags. 7·0 and 8·0, and 811 between mags. 8·0 and 9·0. Treating each group as if all the stars belonging to it were at the same distance from the solar system, the angle OAO′ or the parallactic angle was found to be 3·17″, 2·54″, 2·28″, 1·79″, 1·86″ for the several groups of stars. But in 80 years the actual displacement of the solar system is 320*a*, where *a* is the Sun's distance from the Earth, and thus the average parallaxes of these groups of stars are found by dividing the above angles by 320, and are therefore 0·0099″, 0·0080″, 0·0071″, 0·0056″, and 0·0058″. The distances corresponding to these parallactic angles are 20, 25, 30, 36 and 34 million times the distance of the Earth from the Sun. No stress is to be placed on these exact figures, which are only given to indicate roughly a method by which the distances of the stars may be approximately arrived at.

Another method of obtaining an idea of the distances of the stars is based on the very simple assumption that the density of the stars in space is the same at greater distances as it is near the Sun. If we take a sphere whose radius R is one million times the

Sun's distance, we know that there are 20 stars within this sphere, we should expect to find 20,000 stars within a sphere of radius 10R, and 20 million stars within a sphere of radius 100R. Precise results cannot be given till we are certain that all the stars are known which are within the smallest of these spheres. For this it will be necessary to wait till the results of the organized search for stars of large parallax have been obtained. The simple argument just given shows that while there are only a few stars nearer than a million times the Sun's distance, a very considerable number are within ten times the limit, and probably a large fraction of those visible to the naked eye are within a hundred times this limit.

Only a very rough indication has been given of methods which may be applied with considerable detail. The brightness of a star, other things being equal, is an indication of its distance. Similarly a star with large proper motion is probably nearer than one in the same part of the sky with a small proper motion. It has been established that the stars differ very much in intrinsic brightness, and thus the proper motion generally is a safer guide than the magnitude to the distance of a star. But magnitude and proper motion are not the only classifications which need to be considered in connection with stellar distances. As we shall see later the spectroscope enables stars to be classified according to their physical conditions. Most of the stars fall into one of two types: those

whose spectra exhibit broad lines due to hydrogen and sometimes to helium, such as Sirius, Vega and Rigel, and those whose spectra are, like the Sun, full of metallic lines, such as Capella and Arcturus. It is found that the yellow or solar stars are much nearer to us than the blue or Sirian stars. The following table by Kapteyn gives the mean parallaxes of stars of different magnitudes—

Mag.	Type I.	Type II.
2·0	0·032″	0·072″
4·0	0·016″	0·036″
6·0	0·008″	0·018″
8·0	0·004″	0·009″
10·0	0·002″	0·0045″

The table shows that the mean distance is doubled as we pass from second to fourth magnitude stars, and so on; and that the mean distance of blue stars is more than twice that of yellow stars of the same magnitude. But it must be clearly understood that these are only average results, and that there are great differences in the distances of stars of the same magnitude.

Velocities of the Stars.—It is beyond the scope of this book to go into the rather difficult statistical processes by which the average velocities of the stars are determined. The following table by Professor Newcomb gives in a simple form some of his conclusions. It should be remembered that a velocity of three miles a second would cover the distance from the Earth to

the Sun in one year. Taking 1000 stars, an estimate is made of the number of stars moving 3, 6, 9, etc., miles a second.

Velocity in miles per sec.	No. of Stars.	Velocity in miles per sec.	No. of Stars.	Velocity in miles per sec.	No. of Stars.
0	5	27	75	54	2
3	36	30	59	57	1
6	66	33	44	60	1
9	92	36	32	66	1
12	107	39	22	75	1
15	114	42	14	90	1
18	112	45	9	120	1
21	103	48	6	150	1
24	91	51	3	180	1

As the velocity of the Sun in space is about twelve miles per second, it is seen that the Sun's velocity is rather below the average of stellar velocities.

Absolute luminosity of the Stars.—If the Sun and stars were all at equal distances from the Earth, how would their luminosities differ? It is not easy to determine the ratio with accuracy, but we may take it that the light from the Sun is 40,000,000,000 times the light from the bright star Vega. Now, Vega is of magnitude 0·1, and a little calculation from these figures shows that if the Sun were removed to two million times its distance, when its parallax would be 0·1″, it would appear to us as a star of 5·1 mag., that is to say, would be just visible to the naked eye. As showing how much the stars vary in absolute luminosity the following table

of Professor Kapteyn's may be quoted. In a space containing two million stars of the same luminosity as the Sun there are—

1 star	with	100,000	times	its	luminosity.		
38 stars	,,	10,000	,,	,,	,,		
1800 ,,	,,	1000	,,	,,	,,		
3600 ,,	,,	100	,,	,,	,,		
440,000 ,,	,,	10	,,	,,	,,		

5 million stars with $\frac{1}{10}$th of the Sun's luminosity.
$7\frac{1}{2}$,, ,, ,, $\frac{1}{100}$th ,, ,, ,, ,,

Naturally figures of this kind do not pretend to any great degree of exactitude; but the table given above is based on a careful discussion of such material as exists, and may be taken as an approximate statement of the great diversity which exists in the intrinsic brightness of the stars.

CHAPTER IX

STARS AND NEBULÆ

In the last chapter the questions to be answered were: Where are the stars? and How are they moving? Another series of questions which naturally present themselves are concerned with their chemical and physical nature. What are the stars made of? What are their temperatures? How far do they resemble the Sun and in what respects do they differ from it? Partial answers to these questions can be obtained from a study of stellar spectra, which teach us three distinct things. (1) By comparison with terrestrial spectra something is learned of the chemical composition of the stars. Hydrogen and helium, sodium and calcium, iron and titanium are perceived in stars 100 million million miles away. (2) By slight displacements of the spectral lines from their normal positions, movements in these distant bodies towards or from the Earth are detected and measured. (3) By the differences in character of the spectra, facts about the physical condition of the stars, such as their temperatures and the extent of the atmospheres surrounding them, may be gathered. These three lines of research are not entirely distinct, though they are

so to a large extent. The interpretation of the physical conditions which give rise to the peculiarities in stellar spectra is a matter of difficulty. This is not to be wondered at, for the spectrum of a substance observed in a laboratory differs according to the temperature, pressure, and electrical conditions of the source from which the light is obtained. In the stars these conditions are varied far more than our means of experiment will permit.

Stellar spectroscopy practically dates from 1863 with the researches of Sir William Huggins in England and Father Secchi in Rome. The very considerable difficulties to be overcome arise primarily from the limited quantity of light a star affords. Only a portion of this passes through the narrow slit (say $\frac{1}{200}$th inch wide) of a spectroscope; it is then spread out into a line of several inches in length from the red at one end to the violet at the other; and further, in order to see the structure of the line, it is necessary that it should be broadened into a narrow band by means of a cylindrical lens. When the light is spread out in this way its intensity is greatly diminished.

The introduction of photography made a great advance in the accuracy and the range of stellar spectroscopy. Difficulties still arise, though in another form, from the small quantity of light which is submitted for analysis. Long exposures are necessary, and therefore the light of the star must be kept continuously on the slit of the spectroscope. Further,

the spectroscope must be so mounted that no flexure occurs in the different positions which it takes when the telescope follows the same star for several hours; and again, arrangements have to be made to keep the temperature of the prisms constant (to within a small fraction of a degree), so that their density may not change and give a blurred picture of the spectrum.

As the result of an examination of the spectra of more than 4000 stars, Secchi made an empirical classification of the stars into four types. In the first type he included white and blue stars, such as Vega and Sirius, whose spectra show broad dark lines due to absorption of certain rays by hydrogen. The second type contained yellow stars, like the Sun, Capella and α Centauri, whose spectra show many fine metallic lines and two broad lines in the violet part of the spectrum due to calcium. The third type contained red stars, of which Antares is an example, whose spectra contain a number of dark bands, sharp on the violet side and fading off gradually to the red. The fourth type also consisted of red stars, whose spectra consist of dark bands due to the presence of carbon, sharp on the red side and fading off towards the violet. A fifth type was added later by Messrs. Wolf and Rayet of the Paris Observatory consisting of stars whose spectra contained dark bands and bright lines as well.

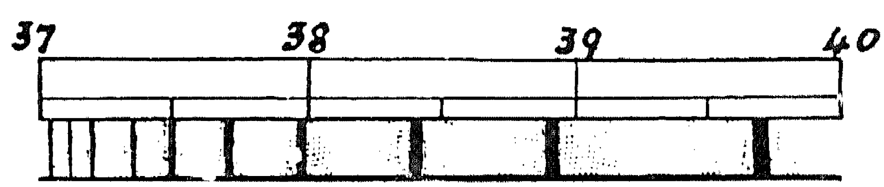
In the Draper catalogue of the Harvard Observatory the spectra of more than 10,000 stars are classified

by Mrs. Fleming. Still more recently, from an examination of 4800 spectra of 681 stars taken with a larger telescope and greater dispersion, a careful and elaborate division of the stars into 22 groups has been made by Miss Maury. This subdivision into 22 groups emphasizes the gradual change from type to type. The most important difference between this and Secchi's classification is the subdivision of the stars of Type I.

All the stars of Secchi's first type are marked by the series of hydrogen lines which gradually close up to a point in the ultra-violet part of the spectrum. About 30 of these lines are seen; they were discovered in the photographs taken by Sir W. Huggins. The wave-lengths were shown by Prof. Balmer to follow a very simple law—

$$\lambda = 3647 \cdot 14 \times \frac{n^2}{n^2-4}, \text{ where } n = 3, 4, 5, 6, \text{ and so on.}$$

The appearance of these broad hydrogen lines in the spectra of certain stars is shown in Diagram LXXVIII.



Diag. LXXVIII.

Helium Stars.—When helium was discovered in 1895 by Sir W. Ramsay, it was found that some of these stars with broad hydrogen lines showed a large

number of helium lines as well. The helium stars also contain lines due to oxygen, silicon and nitrogen. But lines due to metals are found in very few of them. Many of the bright stars of Orion belong to this class, Rigel and Bellatrix among them. Another helium star is β Crucis, in the Southern Cross—the first star in which the presence of oxygen was recognized (by Mr. McClean in 1897).

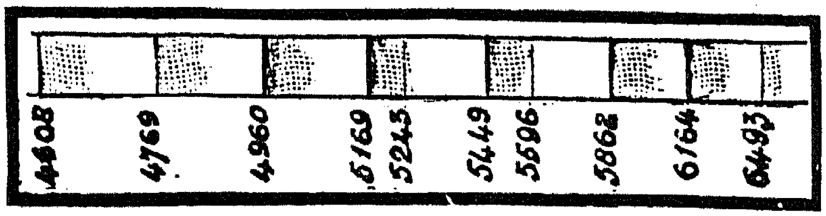
Hydrogen Stars.—Sirius and Vega are the brightest of the hydrogen stars. In the spectra of this group the helium lines are not present. Between the broad lines of the hydrogen series a number of metallic lines are faintly shown in some of the stars. Thus in Sirius are seen lines due to sodium, calcium, magnesium, silicon, iron, titanium, vanadium. Oxygen and nitrogen are not shown.

More than half the stars in the sky belong to Secchi's first type. A remarkable feature about them is their small proper motions, indicating that as a class they are very distant from the Sun. This is specially true of the helium stars. Many of these stars are, however, of very great brilliancy. Sirius, for example, gives us 20 times as much light as the Sun would if placed at the same distance, but is only between two and three times as massive as the Sun. This may result from great intrinsic brightness or very large surface. Again, the blueness of these stars may be taken as evidence that they are not surrounded by a dusky veil like the Sun.

Solar Stars.—The most conspicuous stars of this type are Capella and Arcturus. Their spectra are almost exactly similar to that of the Sun. Procyon and Canopus are intermediate between the Sirian and solar stars, as they show the hydrogen series as well as strong metallic lines. A very large number of stars belong to this group. Some, like Arcturus, are at a very great distance, while *α* Centauri is very near. The similarity of their spectra to that of the Sun shows that these stars are of similar intrinsic brilliancy. The great differences in their apparent brightness is therefore to be attributed solely to distance and actual size. Making allowance for distance, Arcturus is found to be many thousand times more bulky than the Sun, *α* Centauri to be nearly the same size, and some other stars much smaller.

Stars of the Third Type.—When we come to stars of the third type, it is found that a larger proportion of their total light is in the red end of the spectrum—the blue light is absorbed as in solar stars, but to a greater extent. The bands, sharp at their violet edges and fading off towards the red, which are the characteristic feature of this type, have recently been shown by Prof. Fowler to be due to titanium oxide. The same bands have been found by Prof. Hale in Sun-spots. The general appearance of the bands is given in Diagram LXXIX. The existence of an oxide is taken as an indication of comparatively low tempera-

ture. Besides the bands, there are a great many lines due to metals. Antares and Betelgeux, the brightest stars belonging to this type, are at very great distances, and appear to be very much greater than the Sun.



Diag. LXXIX.

Stars of the Fourth Type.—These are comparatively few, and none are brighter than the fifth magnitude. They are characterized by three bands sharp towards the red and fading away towards the violet, which were identified by Secchi as due to carbon compounds. The spectra of this group of stars have been carefully studied by Prof. Hale and Mr. Ellerman at the Yerkes Observatory. They are shown to contain, in addition to the bands, a large number of dark lines and a few bright ones. The presence of sodium and iron, among other bodies, is indicated by the absorption lines.

Stars of the Fifth Type.—The Wolf-Rayet stars have complex spectra, consisting of the superposition of a continuous, bright line and a dark line spectrum. Some of the lines are due to helium and hydrogen, but the rest are unidentified. There are no metallic lines. The brightest star of the class is γ Argus. In it the first line of hydrogen is bright,

the second neutral, and the rest dark. A remarkable feature about these stars is the existence of a series of lines, whose wave-lengths can be derived from the formula for the hydrogen series on p. 196 by giving n the values $3\frac{1}{2}$, $4\frac{1}{2}$, $5\frac{1}{2}$, etc. This points to the existence of hydrogen under conditions which have not been obtained in any laboratory experiments. These Wolf-Rayet stars are all found in the neighbourhood of the Milky Way.

In addition to these stars, Miss Maury has a class whose spectra are like the helium or Orion stars, but in which some of the lines are bright instead of dark.

The following table, taken from the Harvard Annals, shows how the 681 brightest stars between the north pole and 30° S. declination are divided among the different classes—

Helium	117
Intermediate	31
Type I. Hydrogen	185
Intermediate	35
Type II. Solar	218
Type III. Titanium Oxide	55
Type IV. Carbon	4
Type V. Wolf-Rayet	4
Helium stars with some bright lines	14
Composite spectra (probably binaries)	18

The table shows that a very large percentage of the stars are included in the three types of helium, hydrogen and solar stars. The same result is found when the classification is extended to include fainter stars.

Nebulæ.—The relationship of these various classes of stars to one another cannot be understood without reference to an apparently very different kind of body. With his small telescope Halley found two nebulous patches of light in the constellations of Andromeda and Orion. Herschel with his great telescopes discovered thousands of faint nebulous areas. Some were irregular and diffuse, others nearly circular and small. He could not say certainly whether they consisted of faint stars crowded together, or were continuous bodies of luminous fluid. Most of the nebulæ discovered by Herschel are faint and invisible except with large telescopes, so much so that the Bonn Durchmusterung, which contains more than 300,000 stars visible in a small telescope, gives no more than 64 nebulæ.

The key to the nature of these bodies was found by Sir William Huggins in 1864. Light from the brightest of the nebulæ, that of Orion, was collected by the object glass of a telescope, and a small part of it sent through the slit of his spectroscope to be analyzed. The spectrum was not a bright band with dark absorption lines across it like the solar spectrum, but consisted simply of four bright lines, of which the brightest was green. The nebula, therefore, was composed of glowing gas of low density. Other nebulæ were found to contain the same lines, two of which were identified with hydrogen, and the brightest of all was at first thought to be due to nitrogen. Larger tele-

scopes and spectroscopes of greater dispersion have since been employed, and show that this is not the case, and the origin of two of the lines is still unknown. An unknown element *nebulium* may give rise to them, or possibly some known element, but under conditions which have not yet been reproduced in our laboratories. A number of fainter lines have since been discovered in the spectra of nebulæ, among others the yellow line due to helium identified by Prof. Copeland. The most extensive study of nebular spectra has been made at the Lick Observatory by Prof. Keeler, who succeeded in determining the velocities with which 14 were approaching or receding from the Earth, as well as the exact wavelength of nebular lines of unknown origin.

Nebulæ do not all show a spectrum consisting of bright lines. The Andromeda nebula and a very numerous class of spiral nebulæ show a continuous spectrum.

Our knowledge of nebulæ has been largely increased by the beautiful photographs which have been taken in recent years. When a telescope is used with a high magnifying power only a very small area of the sky can be seen at one time. This is of no consequence if we are measuring a close double star or examining a planet, but with extended bodies like some of the nebulæ it is a great advantage to have the whole object before the eye at one time in a photograph. Again, a photographic plate with a

sufficiently long exposure receives impressions which make no perceptible effect on the retina, and thus faint nebulæ and the faint details of bright nebulæ are recorded which could not be observed visually. A third advantage is that the photograph itself is an unbiassed and permanent record of the observations.

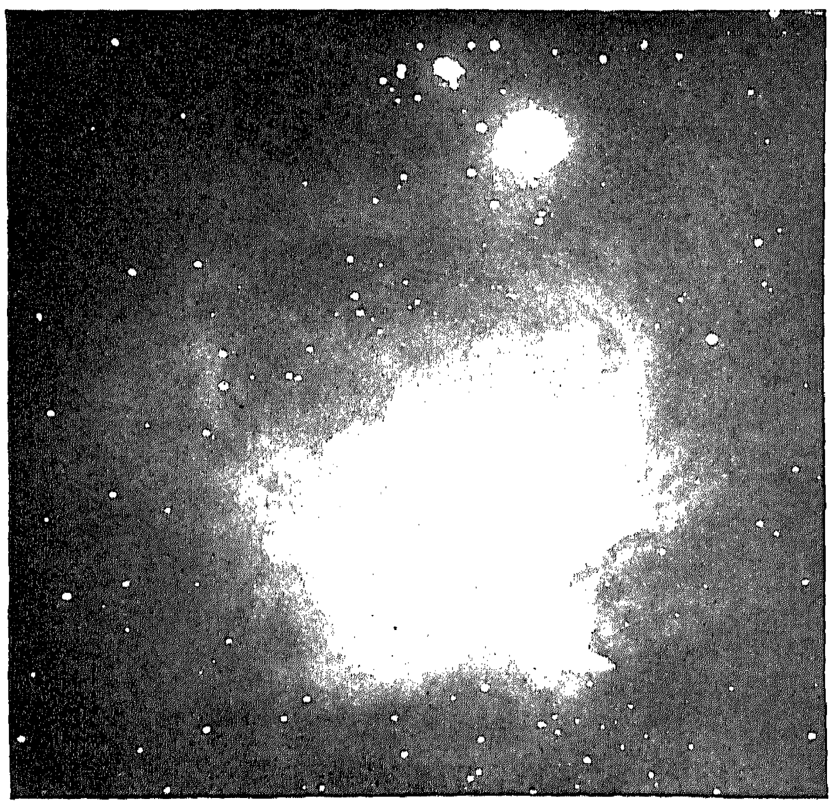
An English amateur astronomer, Dr. Common, succeeded in 1883 in obtaining a beautiful photograph of the great nebula in Orion. He used a large reflecting telescope of his own construction, which possessed great light-grasping power owing to its large size in proportion to its focal length. Following him, Dr. Roberts, another amateur, made an extensive series of photographs of nebulæ, of which he published the most interesting and striking. Many photographs have since been taken at various observatories, either with reflectors or refractors of short focus. A beautiful series of photographs taken by Prof. Keeler at the Lick Observatory, including all the remarkable nebulæ visible in that latitude, has recently been published.

The nebula of Orion is perhaps the grandest object the telescope reveals to us. Its brightest part covers an area of the sky somewhat less than that covered by the Sun. It cannot be less than 10 million times the Sun's distance from us. The distance from one side of the nebula to the opposite side is not less than 10 million million miles, or, comparing with the size of the solar system, 4000 times as large as the distance

from the Sun to Neptune. The tenuity of the nebula must be of a far higher order than any vacua with which we are acquainted, otherwise the mass would produce very great velocities in the stars near it. Some of the stars seen with it appear to be physically connected with the nebula, and not to be merely in the line of vision. This applies especially to four stars forming a trapezium in its brightest part. It was found by Sir W. Huggins that the spectra of these stars contain a number of bright lines identical with some in the nebula. They may have been formed by the condensation of some of the gaseous matter. The displacement of lines in the spectrum shows the distance between the nebula and the Sun to be increasing at a rate of 10 or 11 miles a second. This apparent movement is nearly all due to the movement of the Sun in the opposite direction. There are indications of different velocities in different parts of the nebula, but these are not greater than one or two miles a second. Changes in the luminosity of parts have been suspected, but have not been certainly established. The source of this luminosity (which is excessively small compared with that of the Sun) is unexplained, but there is no reason to suppose that the nebula is at a high temperature. Diagram LXXX, from a photograph taken at Greenwich with a 30-inch reflector and an exposure of 2 h. 15 m., shows the general appearance of the nebula.

The forms of nebulæ have been much better under-

stood since photographs have been obtained. Some are wholly irregular and diffuse, like that of Orion, but several are ring-formed, and a very large number are spiral. Prof. Keeler estimated that in the whole sky there were 120,000 nebulæ of spiral form within



Diag. LXXX.—Orion Nebula.

easy reach of the light-grasping powers of the reflecting telescope of the Lick Observatory.

Although the process is not fully understood, it seems probable that stars have been evolved from nebulæ. The relationship of the stars in the Orion nebula to the nebula itself and the forms of spiral nebulæ confirm the view that the long-continued action of gravitation converts the nebulæ into stars

and stellar systems. The bright line spectra of nebulæ have therefore been taken as a starting-point in classifying the stars according to their order of development. Classifications have been proposed by Huggins, Vogel, Lockyer, and McClean, which differ in some particulars, owing to the difficulty of interpreting spectra. The following is given by Prof. Hale as the one corresponding most closely with current views—

Nebulæ.
Helium stars.
Hydrogen stars.
Solar stars.
Titanium oxide and carbon stars.
Dark stars.

The Wolf-Rayet stars are probably in an early stage of development.

We suppose, then, that a star begins as a nebulous mass. This condenses and forms helium stars, like those found in the centre of the Orion nebula. At first only helium and hydrogen are seen in the spectra, but gradually lines of oxygen, nitrogen, magnesium and silicon are found. Next we come to stars, like Sirius, in which the helium lines are not seen, but where there are broad hydrogen lines, supposed to be characteristic of very extensive atmospheres, as well as fine metallic lines. The study of variable stars shows that hydrogen stars are of much less density than the Sun. It is probable that so far the stars have been getting hotter, for more heat is obtained by contrac-

tion than is lost by radiation, as long as a star remains gaseous. After the hydrogen stars, the order proceeds through stars like Procyon to Capella and Arcturus, which resemble the Sun. The spectra of these yellow stars is marked by the number of metallic lines, the disappearance of all but the first five of the broad hydrogen lines, and the prominence of two calcium lines in the violet. Further, an absorbing atmosphere, like the dusky veil round the Sun, cuts off a large amount of the violet and blue light. Next we come to the red stars, in which the absorbing atmosphere has grown more intense and cuts off still more of the blue light. The presence of compounds with fluted spectra shows that these stars are of lower temperature than the solar stars, and are declining to the stage of dark stars. There are no doubt differences in the evolution of different stars. A large star will probably be longer in going through its stages than a small one. Of the length of time occupied we have no idea.

CHAPTER X

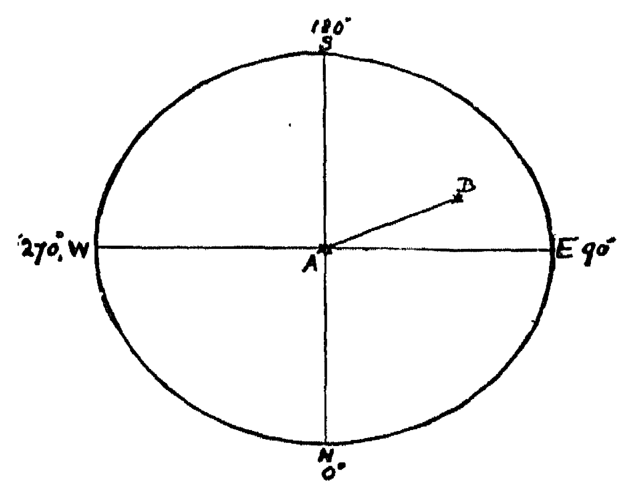
DOUBLE STARS AND CLUSTERS

Sir William Herschel is generally spoken of as the founder of Sidereal Astronomy. He took for his motto "Whatever shines should be observed," and constructed telescopes far surpassing in light-grasping and penetrating power those of his predecessors, with which he executed a most thorough and minute exploration of the sky. Herschel was, in addition, a philosopher who interpreted what he saw with the consistent aim of obtaining as completely as possible a rational description of the sidereal universe, but it is to his persistence and enterprise as an *explorer* of the skies that the discovery of double stars is due.

While making an examination of the sky for the purpose of finding some stars of measurable parallax, he discovered that many stars were double, and in 1782 presented to the Royal Society a catalogue of 269 double stars. He supposed at the time that these were only optically double, that is, were nearly in the same line as seen from the Earth. His intention was doubtless to see if in any cases a movement of the brighter star relative to the fainter, such as would arise from their different distances, could be discerned

in the course of the year. He was, in fact, seeking to determine the parallax of a star, in the way which was successfully carried out by Bessel in 1831, and which is described in Chapter VIII.

The observation of a double star will be understood from Diagram LXXXI. If A and B are the two stars, the distance AB between them is measured, and also the angle BAN, between the line joining the stars and the meridian through the star A. By 1803 Herschel had sufficient evidence that some of the stars he had observed were not double in appearance only, but were real binary combinations of two stars, held together by the bond of mutual attraction. The bright star Castor first convinced Herschel of the existence of double stars with orbital motion about one another. In the space of 22 years the direction of the line joining the stars had changed by more than 20°. (Castor is easily seen to be double with a small telescope; the distance between these two stars is about 5″; both are bright, one being of mag. 2·7 and the other 3·7.) Herschel concluded that the stars revolve round one another in 342 years. Similarly he found for γ Leonis a period of 1200 years, for δ Serpentis 375 years, for ϵ Boötis 1681, and for γ

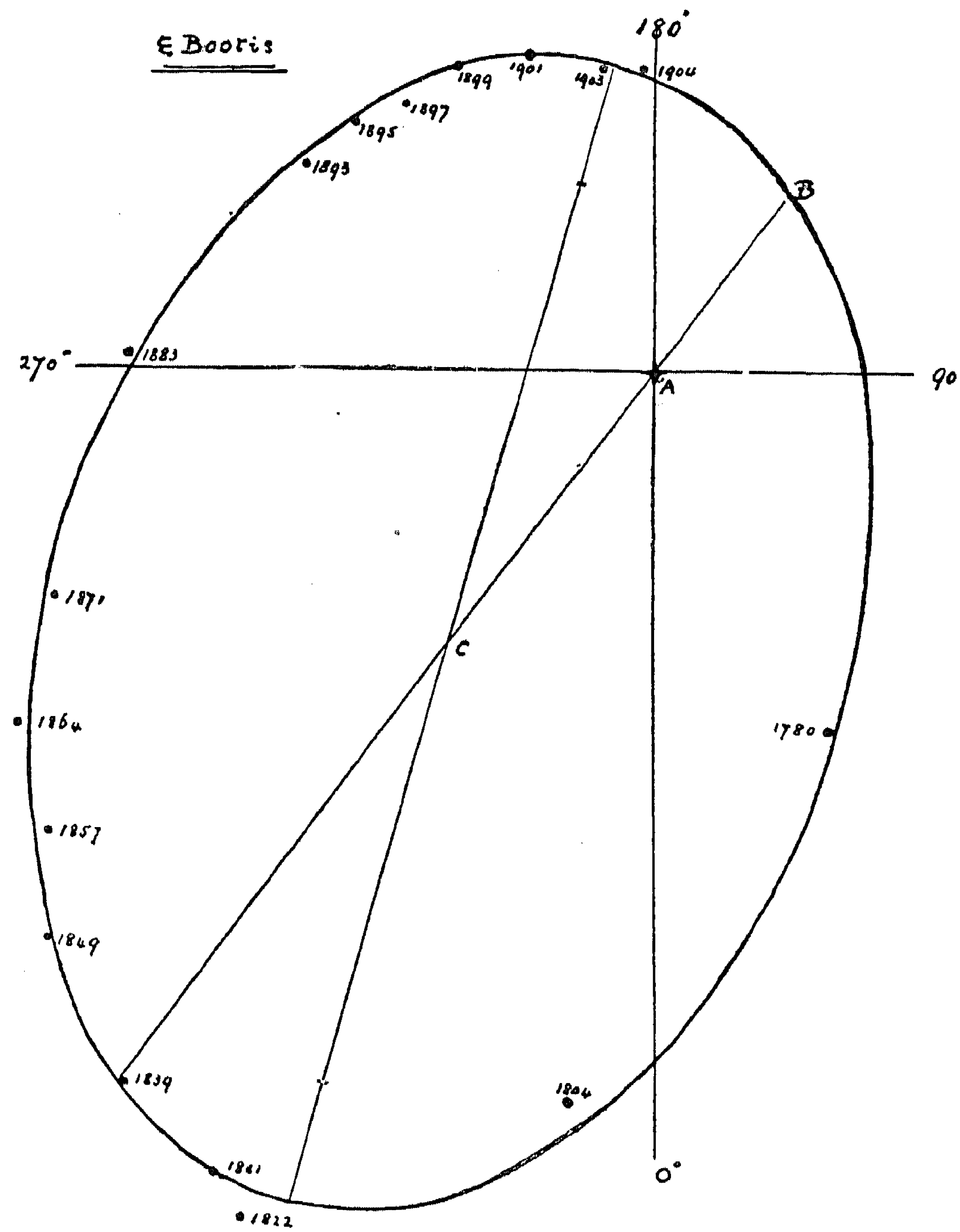


Diag. LXXXI.

Virginis 708 years. He also found that ϵ Lyræ is a double double star. Herschel's work was continued by his son, and by Sir John South, but most of all by Wilhelm Struve at Dorpat. Struve made measures of all stars he knew to be double, and in addition made a minute review of the heavens from the north pole to 15° south of the equator. He examined 120,000 stars, and produced a great catalogue containing 2640 double stars. Since Struve's time the number of astronomers who have given attention to the observation of double stars is considerable, and has included some of exceptionally keen eyesight. With the assistance of larger telescopes the scrutiny of the stars has been pushed further, so that very faint companions to bright stars have been discovered, and many which with small telescopes appear to be single, have been resolved into very close double stars. Especially conspicuous is the work of Prof. Burnham at various observatories in the United States, and of his successors, Profs. Hussey and Aitken, at the Lick Observatory.

During the time they have been under observation, some double stars have made a complete revolution about one another, and in many cases sufficient movement has taken place for an accurate determination of the period or time of revolution. The shortest period as yet found is about $5\frac{1}{2}$ years. There are a considerable number whose periods are between 20 and 50 years, and a great many whose periods are hundreds

of years. The orbit of ξ Boötis, shown in Diagram LXXXII and taken from a work by Mr. T. Lewis on



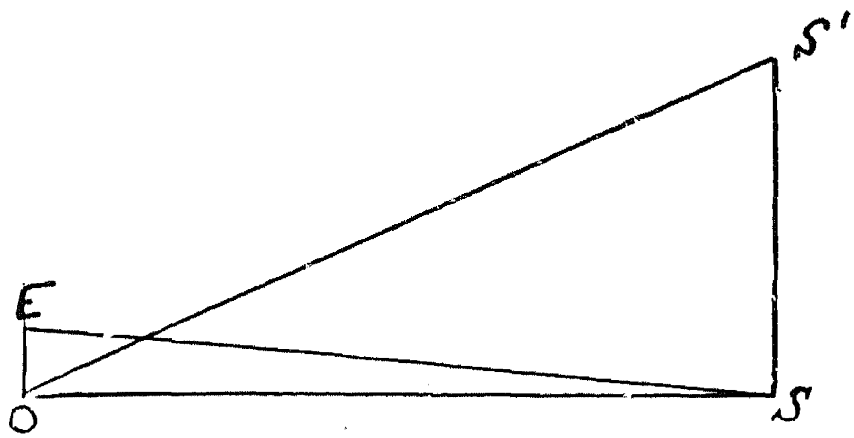
Diag. LXXXII.

the double stars observed by W. Struve, may be considered as that of a typical double star whose components are fairly widely separated. The brighter star of

the pair at A is of magnitude 4·7, and of yellow colour; the companion is of magnitude 6·6, and is purple. The relative positions of the stars as seen by Herschel in 1780 and 1802, by Struve in 1822, and subsequent observers, are indicated by dots. These dots all lie on an ellipse, but it is not an ellipse with A as focus, for we see not the true orbit of the star about its primary, but the projected orbit on a plane perpendicular to the line joining the Earth and the star. The true orbit may be determined from the apparent one by calculation. In the case of ξ Boötis the complete revolution will be accomplished in about 137 years. The length of the major axis of the apparent orbit is 9·60″, and of the minor axis 5·61″, and calculation shows that the major axis of the true orbit is 10·66″, the minor axis 8·53″, and that the true orbit is inclined at an angle of about 50° to the apparent orbit.

When the distance of a double star from the Earth is known, it is possible to determine the actual distance between the stars. Take, for example, the bright star Sirius, which has a very faint companion. The parallax of Sirius is known to be 0·37″, and the semi-major axis of the orbit of the companion around Sirius is approximately 8·0″. Construct a diagram (Diagram LXXXIII) in which ☉ stands for the Sun and S for Sirius, and let ☉S denote the distance of the Sun from Sirius. Draw ☉E perpendicular to ☉S, and make ☉E equal to the Earth's distance from the

Sun on this scale. Similarly let SS′ denote the semi-major axis of the orbit of the companion about Sirius on the same scale. Then



Diag. LXXXIII.

$$\left.\begin{array}{r} \text{the angle } ES\odot = \text{ parallax of Sirius} = 0{\cdot}37'' \\ \text{and the angle } S\odot S' = \text{semi-major of orbit} = 8{\cdot}0.'' \end{array}\right\}$$

From which it follows that $SS' : \odot E = 8{\cdot}0'' : 0{\cdot}37''$, or that the semi-major axis of the orbit is $\frac{8{\cdot}0}{{\cdot}37}$, or 22 times the Earth's distance from the Sun. Thus the linear dimensions of the orbit of the faint companion around Sirius are known.

Further, the combined mass of the bright star and its companion can be compared with that of the Sun. The attraction of the Sun causes the Earth to make its revolution in one year. The companion of Sirius takes 50 years to go round Sirius, and its mean distance from Sirius is 22 times that of the Earth from the Sun. As we have seen in Chapter III (p. 52), we can from these data find the sum of the masses of Sirius and its companion. Calling them m and m',

and that of the Sun M, we have the equation $\frac{m+m'}{M} = \left(\frac{22}{1}\right)^3 \cdot \left(\frac{1}{50}\right)^2 = 4{\cdot}3$, or the sum of the masses is 4·3 times that of the Sun.

In the case of Sirius and a number of other double stars it is possible to compare the masses of the primary star and of its companion. This, however, requires other observations than the relative movements of companion and primary afforded by double star measurements. In these measures the companion is considered as describing an ellipse about its primary, whereas both the primary star and companion are describing ellipses about their common centre of gravity. Before the companion of Sirius was discovered it was known to exist, because Sirius was seen to have a slightly irregular movement in the sky. In addition to its proper motion in a straight line, it was seen to be describing a small ellipse in 50 years. In 1844 Bessel was convinced that the explanation of this elliptic movement of Sirius was to be attributed to an invisible but massive companion. In 1862 Mr. Alvan G. Clark, while testing an object glass of 18 inches aperture by examining the appearance of Sirius with it, discovered this faint companion. It was only of the tenth magnitude, and thus 16,000 times fainter than Sirius, and at the time of discovery was 10″ distant. When the meridian observations which had indicated the movement of Sirius about its centre of gravity were investigated in 1864 by Dr. Auwers, it

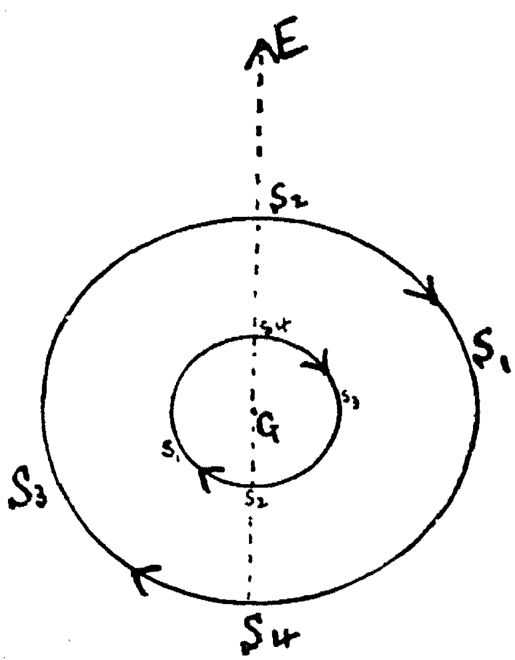
was found that the bright star described an ellipse whose semi-major axis was 2·33″. Thus in Diagram LXXXIV, where S is Sirius, S′ the faint companion,

Diag. LXXXIV.

and G the centre of gravity, SG = 2·33″ and SS′ = 8·00″, and therefore S′G = 5·67″. The mass of the faint companion is therefore greater than that of Sirius in the proportion of 5·67″ to 2·33″, or about $2\frac{1}{2}$ to 1. Taking the total mass to be 4·3 times that of the Sun, we see that Sirius itself is about 1·2 times the mass of the Sun, and the dark, almost invisible, companion is rather more than 3 times. In other cases where it has been possible to compare the bright and faint components of a double star, the faint component has usually been found to be the more massive.

Spectroscopic Binaries.—Sirius and Procyon were shown to have invisible companions from their variable motion on the face of the sky. In a large number of cases stars which are apparently single have been shown to be double by variations disclosed by the spectroscope in the velocity of the star to or from the Earth. Let us consider the simplest case. Suppose there are two stars, S and *s* (Diagram LXXXV), which are describing circles about their centre of gravity, G, and suppose the Earth to be in the same plane as their orbit in the direction GE, but so far away that the stars appear single in the largest telescope. When the star S is at S_1, S_2, S_3, S_4, the companion will be

at s_1, s_2, s_3, s_4, so that the line S*s* always passes through G. Further, for simplicity, let us suppose that G is at rest relative to the Earth. When the star S is at S_1 it is moving away from the Earth, and the lines of its spectrum will be shifted from their normal position towards the red end of the spectrum, and from the amount of this shift the velocity of S can be determined. At the same time the star *s* is at s_1, and moving towards the Earth, the lines of its spectrum will be shifted towards the violet from their normal positions by an amount which measures the velocity of *s*. When S is at S_3, and *s* is at s_3 the conditions will be reversed. At the intermediate points when S is at S_2 or S_4, and *s* at s_2 or s_4, the stars have no velocity to or from the Earth, and the lines in their spectra will not be displaced from their normal positions.



Diag. LXXXV.

When the spectrum of a binary star which is seen single in the telescope is photographed, the result is the same as if the spectra of two separate stars had been photographed on the same plate. It may happen that S is a bright star and *s* a very faint one,

in which case the spectrum of *s* will not be recorded. Again, it is possible that S and *s* may be two stars of nearly equal magnitude and similar spectra, in which case, owing to the shift of the lines due to the motion of the stars, lines in the spectra will sometimes appear doubled. A third possibility is that S may be a star giving an entirely different spectrum from *s*, in which case two separate spectra are superposed. But in all cases photographs of the spectrum of a binary star, taken when the components are in different relative positions, will show displacements of the lines due to the varying velocities of the stars in the direction of the Earth.

A large number of stars have proved to be spectroscopic binaries. Some have been discovered from the composite character of their spectra, which looked like the spectra of stars of two different types on the same photograph. Others have been discovered in the course of measurements of the positions of lines in spectra made with the intention of determining the velocity of the star to or from the Earth. The spectra obtained on different days have given different results, and subsequent photographs have shown the changes to be regular, and such as can be accounted for by supposing the stars to be binaries.

The spectrum of Mizar (ζ Ursæ Majoris), a bright star of the Great Bear, was found by Miss Maury to have the K line (due to calcium) double on two photographs taken at Harvard in 1887 and 1889, but

single on other photographs. Examination of 72 photographs showed that the changes in the spectrum occur at regular intervals, and were explicable if Mizar consists of two stars which revolve round one another in 104 days. Further, the relative velocity of the two stars was found to be about 100 miles per second. Assuming them to be of equal mass, and that the plane in which they move passes through the Earth, the two components are 140 million miles apart, and their combined mass is 40 times that of the Sun.

In 1890 Vogel found that Spica was a spectroscopic binary. In this case the star consists of the bright star we see and a dull but massive companion. The displacements of the lines in its spectrum from their normal positions are completely explained on the assumption that Spica revolves about its companion in 4 days approximately with a velocity of 57 miles a second if the plane of the orbit passes through the Earth. If the orbit is inclined to the direction joining the Earth and star, as it is certain to be to a greater or less extent, the velocity will be greater than 57 miles a second, as the spectroscope only appreciates that part of a star's velocity which is directed to or from it.

Another interesting spectroscopic binary is Capella. In 1900 Prof. Campbell at the Lick Observatory, and Prof. Newall at Cambridge, independently found that Capella consists of two stars, one like the Sun in type of spectrum, and the other like Procyon. These

two stars revolve about one another in a period of 104 days.

The following example, *a* Carinæ, discovered by Mr. Wright in the course of a Lick Observatory expedition to the southern hemisphere, is a fairly typical case. From photographs of the spectrum of this star on 25 nights the following velocities were found in kilometers per sec. (1 km. = $\frac{5}{8}$ mile)—

Date.	Vel.	Date.	Vel.
1904 Feb. 29.67	+ 5·7	1907 Feb. 6.67	+ 2·0
1905 Jan. 30.68	+ 33·2	19.73	+ 1·9
Feb. 9.64	+ 10·0	Mar. 2.74	+ 41·3
Feb. 22.62	+ 4·6	4.74	+ 16·7
Mar. 7.58	− 1·2	14.63	+ 25·7
1906 Mar. 30.58	+ 3·0	16.63	+ 44·3
1907 Jan. 15.79	+ 39·0	19.57	+ 5·2
19.81	+ 31·1	23.53	+ 40·8
21.76	+ 44·4	24.58	+ 28·8
25.81	+ 18·6	Apr. 30.49	+ 20·4
26.79	+ 31·2	May 1.49	+ 35·2
Feb. 2.75	+ 31·8	11.48	+ 5·7
5.77	+ 16·2		

From these figures the period during which these fluctuations occur is found to be 6·744 days; the velocity of the centre of gravity of the system away from the Sun is + 23·3 km. per sec.; and the velocity of the bright component of the star varies from 0 to + 43 km. per sec.

In the last few years a very large number of spectroscopic binaries have been discovered, especially with the large telescopes of the Lick and Yerkes Observatories, with their spectroscopes of great re-

solving powers. In 1898 thirteen spectroscopic binaries were known. The number discovered to the end of 1905 was 140, and since that date the number has been nearly doubled. Prof. Campbell found one star in seven of those studied at the Lick Observatory to be a spectroscopic binary. The larger proportion of one in three was found by Prof. Frost at the Yerkes Observatory in the particular class of stars he was studying. In most cases the spectrum of only one component is visible, so that these binary stars like Sirius consist of a bright star with a dull but massive companion.

Clusters.—It has frequently happened in the course of double star observations that one of the two components has itself been found to be double. For example, γ Andromeda was found by Herschel to consist of two stars of magnitudes 2·5 and 5·5 about 10″ distant. Otto Struve found that the fainter component, when examined with a very large telescope, was itself a very close double star. In this way we have become acquainted with systems consisting of 3 or 4 stars. But the sky contains groups of stars on a much grander scale. The Pleiades are one of the most familiar examples. In this collection of stars six are bright enough to be seen by most people with the naked eye, and six or seven more are visible to persons of specially keen sight, while a great many more are shown by an opera glass or small telescope. It is found that the brighter stars

among the Pleiades, and many of the fainter ones, have the same proper motion of 7″ a century. They therefore form a group of stars moving together in space, and are not a mere optical group because they happen to lie nearly in line as seen from the Earth. The brighter stars have similar spectra, and the whole group is found by photographs taken with long exposures to be involved in a faint nebula.

In Sir John Herschel's catalogue of nebulæ in 1864 he includes 110 globular clusters of stars. In these clusters the stars are seen much nearer together than in the Pleiades. With a small telescope they cannot always be separated, and the cluster might be taken for a nebula; but with a larger telescope they are resolved into separate stars. Diagram LXXXVI, from a photograph with the great refractor of the Yerkes Observatory, taken by Prof. Ritchey, shows the appearance of the cluster in Pegasus. The stars are small and concentrated in the centre. The num-

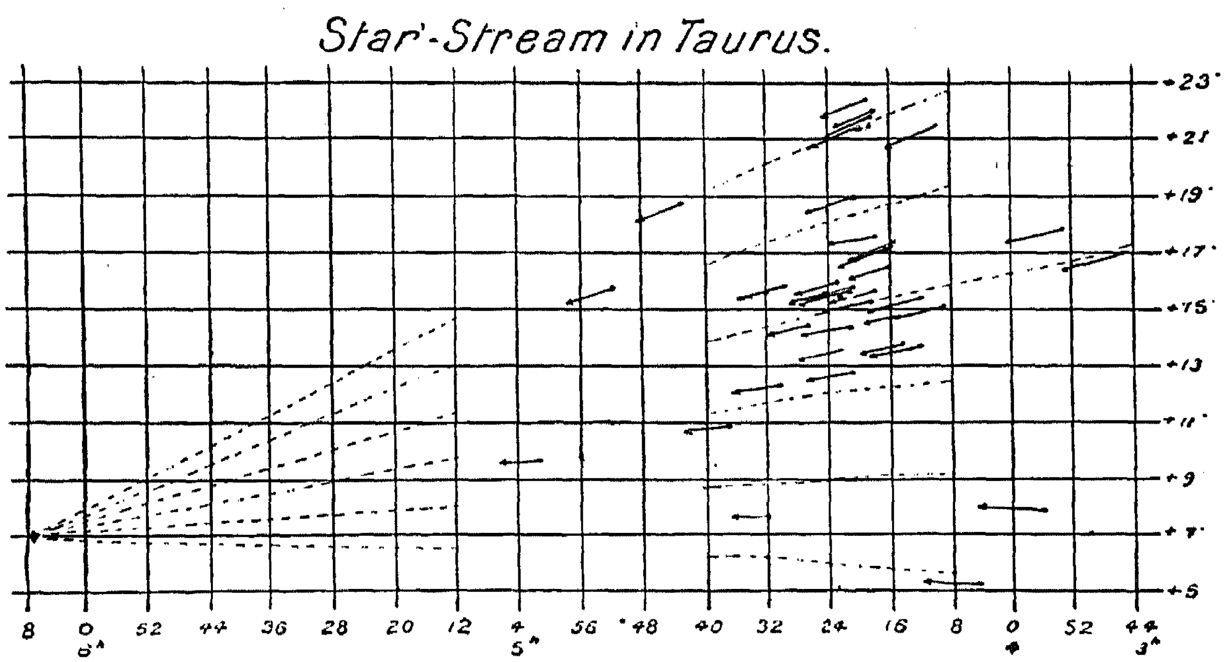
Diag. LXXXVI.—Cluster of Stars.

ber of stars in some of these clusters have been counted. In a photograph of the southern cluster round ω Centauri, Prof. Bailey found more than 5000 stars in a small area occupying about as much space as the Sun or Moon in the sky. Till we know the distance of the cluster it is impossible to say how far the stars in it are apart.

A curious feature about the globular clusters of stars is the large percentage of short period variables (see Chapter XI). Thus in the cluster illustrated above out of 500 stars 91 are variable.

In 1908 Prof. Boss pointed out that about 40 bright stars in and near the constellation Taurus form a small globular cluster, which is sufficiently near for us to see inside, so to speak, and learn its dimensions. Investigations of proper motions prove that these 40 bright stars, of magnitudes 4·0 to 6·5, are moving towards one point in the sky. Diagram LXXXVII shows the direction of motion, the length of the arrows indicating the angular distance travelled in 50,000 years. Apparent motion towards one point in the sky results from parallelism in the actual paths of the stars. The amount of proper motion, that is, projected angular motion on the face of the sky, is known for each star, and for three of them the velocity in the line of sight is also known. These facts are sufficient to show that these 40 stars are all moving in parallel directions towards a point RA 6 h. 52 m.; Dec. $+7^{\circ}$ with a velocity of

28½ miles a second, and to determine the distance of each star from the Earth. The stars form a cluster of roughly globular shape. The centre of



Diag. LXXXVII.

the cluster has a parallax of about 0·025″, corresponding to a distance of about 8 million times the Sun's distance. The distance of outlying stars in the cluster from one another is about 2 million times this distance, so that the cluster is packed about as loosely as the Sun and its nearest stellar neighbours. The cluster was nearest to the Sun about 800,000 years ago, when it was at half its present distance. It is moving rapidly away, and will gradually assume the more compact appearance of a globular cluster, which in 65 million years will be only 20′ in diameter, and consist of stars of 9th to 12th magnitude. Besides these 40 stars, 50 fainter stars of magnitudes

6·1 to 7·5 probably belong to the cluster, and doubtless some still fainter ones will be discovered. To confirm Prof. Boss's results, the velocities in the line of sight of more stars in the cluster are being determined at the Yerkes Observatory. The curious fact has appeared that the stars are of Secchi's first type (hydrogen) and that 8 out of the 14 examined have proved to be spectroscopic binaries.

CHAPTER XI

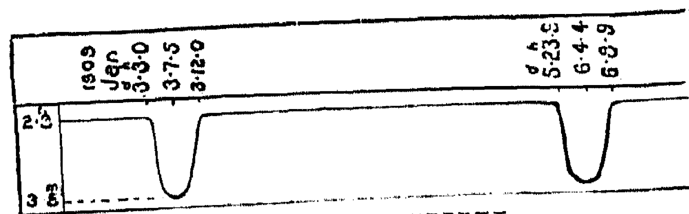
VARIABLE STARS AND NEW STARS

Variable Stars.—The discovery was made in 1596 by Fabricius that the star *o* Ceti varies in brightness. Sometimes this star is easily visible to the naked eye, but at other times it is as faint as the eighth or ninth magnitude, and can only be seen with a telescope. Other variable stars were gradually discovered, and in 1844 Argelander published a catalogue giving particulars of the 18 stars which were then known to be variable and urged the importance of studying these bodies in detail. A great deal of attention has been given to variables since this date, and in recent times the information acquired by studying the variation of their light has been supplemented by that afforded by the spectroscope. The number of stars known to be variable has increased greatly, and in 1907 Prof Pickering of Harvard published a catalogue of 374[illegible] of these bodies. He divides variable stars into five classes, and though the distinction between them is not absolute, this subdivision is rendered necessary by the well-marked differences between them.

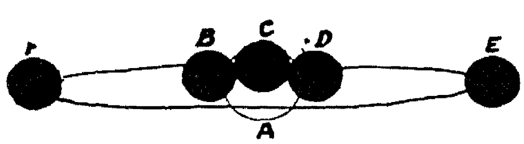
Eclipsing Stars.—Algol or β Persei is the best known type of this class. Its changes of brightness are

regular and are repeated after a period of 2 days 20 hours 49 minutes.

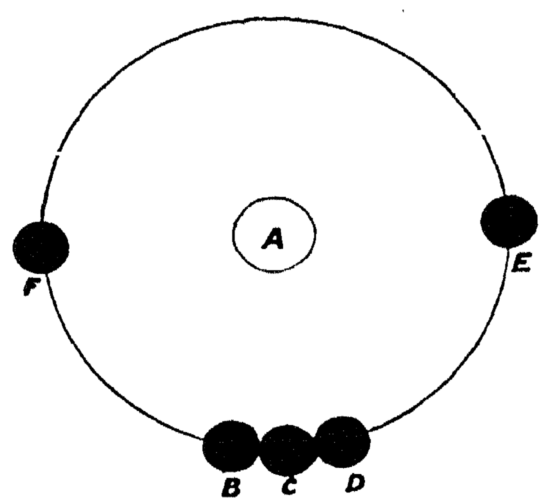
For $2\frac{1}{2}$ days the brightness of the star remains constant (2·3 mag.); in $4\frac{1}{2}$ hours it falls to 3·5 mag., and in the next $4\frac{1}{2}$ hours returns to 2·3 mag. When at its faintest Algol shines with only one third of the light it has in its brightest phase. These variations in magnitude are shown graphically in Diagram LXXXVIII, from which the magnitude at any time between January 3 d. 3 h. and January 5 d. 25 h., 1910, may be inferred.



Diag. LXXXVIII.
Light changes of Algol.



Diag. LXXXIX.



Diag. XC.

Goodricke, who discovered the law of change in the brightness of Algol, suggested that the star possesses a dark companion, which periodically intervenes between Algol and the Earth and cuts off a part of the light. Diagrams LXXXIX and XC illustrate exactly how this occurs. In Diagram LXXXIX the observer

is nearly in the plane of the orbital motion of the two stars, as is really the case, while Diagram XC shows the plan of the orbit. A is the bright star; B, C, D, E, F, are the dark star in different positions. When the dark star is at B, C or D part of the light from A is intercepted.

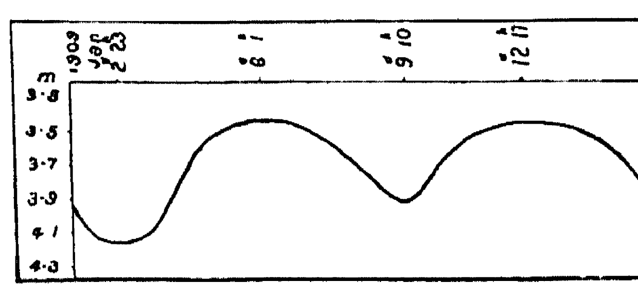
In 1889 Prof. Vogel examined Algol spectroscopically, and completely established the fact that the variation of light is caused by a dark eclipsing satellite. If the bright star Algol has a dark companion they will revolve about their common centre of gravity. After the dark star has passed in front it will be moving away from the Earth and the bright star towards the Earth, and the maximum velocity will be, if the orbit is circular, one quarter of the entire period of revolution, or 17 hours after the epochs of minimum brightness. Similarly the maximum velocity of the bright star from the Earth should occur 17 hours before the epochs of minimum brightness. The spectroscope confirmed these surmises, and showed that 17 hours before mid-eclipse Algol is moving towards the Sun with a velocity of 39 kilometres per second, and 17 hours after mid-eclipse from the Sun with velocity 47 kilometres per second. These figures show that Algol and its companion are moving from the Sun with a velocity of $\frac{47-39}{2}$ or 4 kilometres per second, and the velocity of Algol in its orbit is $\frac{47+39}{2}$ or 43 kilometres per second, and, as

we have seen, the time of describing the orbit is 2 days 20 hours 49 minutes.

From the loss of light experienced at mid-eclipse, the ratio of the diameters of the bright and dark stars may be inferred. From the ratio of the period of the eclipse to the period of revolution, the sum of the radii of the stars can be compared with the distance between their centres. Since the bright star is moving 43 kilometres or 28 miles a second and takes 2 days 20 hours 49 minutes, or nearly 250,000 seconds, to complete its circle about the centre of gravity of the two bodies, the radius of this circle will be rather more than one million miles. It is necessary now to make some assumption about the relative masses of these two stars, and Vogel, taking them to be of equal density, concludes that Algol is one million miles in diameter or 1·2 times the size of the Sun, the companion 800,000 miles, or about the size of the Sun, and that the distance between the centres is 3,200,000 miles.

Between 30 and 40 variable stars resemble Algol. The period of variation is generally short, less than 5 or 6 days, and the time of eclipse lasts for some hours. The bright and dark star are very close together in comparison with their diameters, as would naturally be expected, for otherwise the chance of the Earth being near enough to the plane of the orbit to witness eclipses would be very small. A remarkable feature in all these stars is their small mean density. In the case of Algol, for example, this is not more than $\frac{1}{4}$ of the density of water.

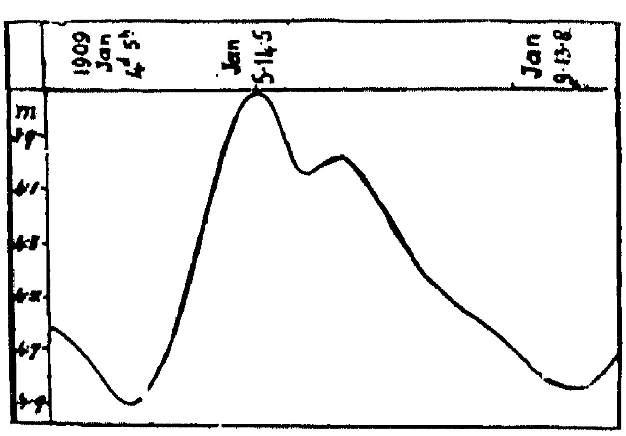
Short-period Variables. — The characteristic of the variables whose periodic changes of brilliancy can be explained by the revolution of a bright and dark star around one another is the maintenance of the maximum brightness for a large part of the whole period. The stars belonging to the second class change their light continuously. Sometimes in a complete period there are two maxima and two minima, sometimes only one. The changes of brightness generally occur in a space of less than 10 days and very rarely take more than one month. At least 60 or 70 variables are known to belong to this class. The three stars β Lyræ, δ Cephei and ζ Geminorum may be taken as examples. β **Lyræ** goes through its changes in 12·9 days, having two maxima of magnitude 3·4, a primary minimum of magnitude 4·2, and a secondary one of magnitude 3·9. Its four phases of increasing and decreasing brightness are approximately equal. The variability of the star has been known since 1784. The spectrum is difficult to interpret owing to the juxta-position of bright and dark lines and also on account of its variability. The changes which the spectrum undergoes have the same period as the light-variation. Some of these changes are explicable on the hypothesis that two stars are revolving round each other. From a very elaborate investigation of the variation of



Diag. XCI.
Light changes of β Lyræ.

magnitude and changes in the position of certain lines in the spectrum observed by Prof. Belopolsky and Sir N. Lockyer, Prof. Myers of Indiana has deduced that the star consists of two large gaseous bodies very near together which revolve round one another. They are not quite spherical but owing to mutual gravitation are spheroidal. The smaller is 2½ times as bright as the larger and half as massive. The distance between their centres is 50 million miles, and the orbit they describe about one another is nearly circular. As the Earth is nearly in the plane of the orbit, in the course of a revolution first one body and then the other is partly hidden and the dimensions given are such as will account numerically for the changes of brightness. The spectroscope shows the stars to be gaseous, but Prof. Myers' figures give the astounding result that the mean density of the system is a little less than that of air.

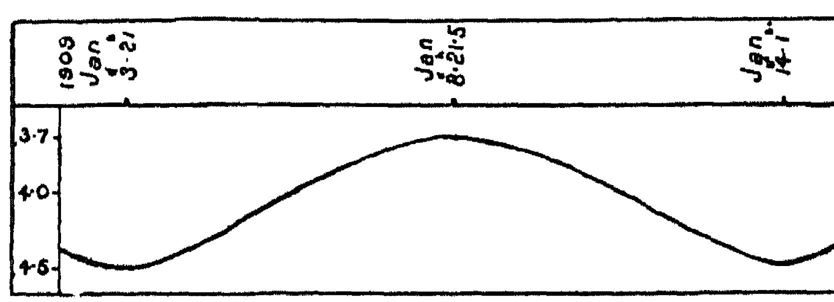
δ **Cephei.**—The light curve of δ Cephei is very typical of short-period variables. The period of the light changes is 5 days 8 hours 47 minutes 40 seconds, but the time taken for the brightness to rise from the minimum to the maximum is much shorter than for the fall. In 1894 this star was shown by Belopolsky



Diag. XCII.
Light changes of δ Cephei.

to be a spectroscopic binary, whose changes in velocity had the same period as the light changes. The spectrum of only one component is shown. The star is found to be moving in a very eccentric orbit, and if it exhibited no variation of light would be set down as a spectroscopic binary consisting of a bright and dark star. But the changes of light cannot be accounted for in this way, for it is found that the minimum brightness occurs a day before the time when the two stars are in line as seen from the Earth. The light variation cannot, therefore, be explained as due to an occultation of one star by another, and no satisfactory explanation has been given.

ζ Geminorum.—This star goes through its phases in 10 days 3 hours 41 minutes 30 seconds. At its minimum the magnitude is 4·5 and at maximum 3·7. The time during which the brightness increases is almost equal to the time during which it decreases. Forty-four photographs of the star's spectrum were taken at the Lick Observatory between November 11, 1898 and February 11, 1900. These showed that the star is a spectroscopic binary, of which one component is bright and the other dark. The changes of velocity occur in the same period as the light changes.



Diag. XCIII.
Light changes of ζ Geminorum.

From the measures of velocity the orbit of the star was determined, but as in the case of δ Cephei the time when the two stars are in line as seen from the Earth does not coincide with the time when the brightness is a minimum. The light variation does not therefore result from an eclipse. Some peculiarities in the velocities derived from the spectra suggest that as the dark and bright body are very close together, large tidal effects may be produced in the atmosphere of the bright star, and that the explanation of the light changes is to be looked for in causes of this nature.

In the variables of short period it is clear that we are dealing with bodies of large size and small density. There can be no doubt of their essentially binary character. The two components appear to be very close together and may in some cases be joined by a neck. Possibly these variables present to us different stages in the segmentation of nebulous matter which is forming into two stars, the Algol class showing a further stage of this development. Such a view is, however, extremely speculative, as very little is known of the dynamical conditions to which such nebulous matter would be subject.

Long-period Variables.—When a star is variable in a short period of less than a month, we have seen that the explanation is probably to be looked for in the rotation of two very close bodies. There are a large number of stars whose period of variability is much longer. More than 300 are known whose

periods lie between 200 and 400 days, and a considerable number beyond these limits. These are all classified as variables of long period. The difference in magnitude between these stars at their brightest and faintest is often very great—a difference of 5 magnitudes or a variation of light in the proportion of 100 to 1 being not at all unusual. Generally speaking, the longer the period the greater the difference between the extreme magnitudes. These stars do not go through their variations with the same regularity as the variables of short period. The brightness at maximum varies from time to time, and the length of the period is not exactly the same from each maximum to the next. Many of these stars are red or reddish.

The most famous star of this class is *o* Ceti, or Mira Ceti as it was called by Hevelius. In about 332 days it increases in brightness from below the ninth magnitude to about the second and then diminishes again. Its variations have been watched for 200 cycles, and its period has been seen to vary from 320 to 370 days, but no law has been discovered for these changes. The greatest brightness the star attains also varies considerably. In 1779 Herschel saw it rise to magnitude 1·2; in 1868 it was only of magnitude 5·6 at maximum; in 1897 it reached the third and in 1905 the second magnitude. Similarly its brightness at minimum has varied from 8·0 mag. to 9·5 mag.

The spectrum of Mira Ceti has been studied by

many astronomers. It consists of bright lines and dark bands. The dark bands are those found in stars of Secchi's third type, due to titanium oxide, while the bright line spectrum contains lines due to hydrogen and some metallic lines. The relative intensities of the bright lines vary in different parts of the star's cycle. There are no changes in the spectrum that suggest orbital motion. It would seem that there are periodically great outbursts of incandescence in the star itself. The changes which occur in long-period variables bear a resemblance to the periodic changes in the amount of the Sun's area covered with spots. The sun-spot period is long—about 11 years—and irregular. Sun-spot and long-period variables show the banded spectrum of titanium oxide. These suggest that long-period variables may be stars which are periodically largely covered by spots.

New Stars.—Passing over another group of variable stars in which the light fluctuates in an altogether irregular manner we come to a very remarkable class which bear some resemblance to variables of long period. These are the *new* stars. Hipparchus, Tycho Brahe, and Kepler all witnessed with astonishment the appearance of new stars in the sky. Two were seen in the seventeenth century, and eight in the nineteenth, while in this century two have been found, one by Dr. Anderson at Edinburgh, and one photographically by Prof. Turner at Oxford. The new stars from which most has been learned are Nova Aurigæ of 1892 and

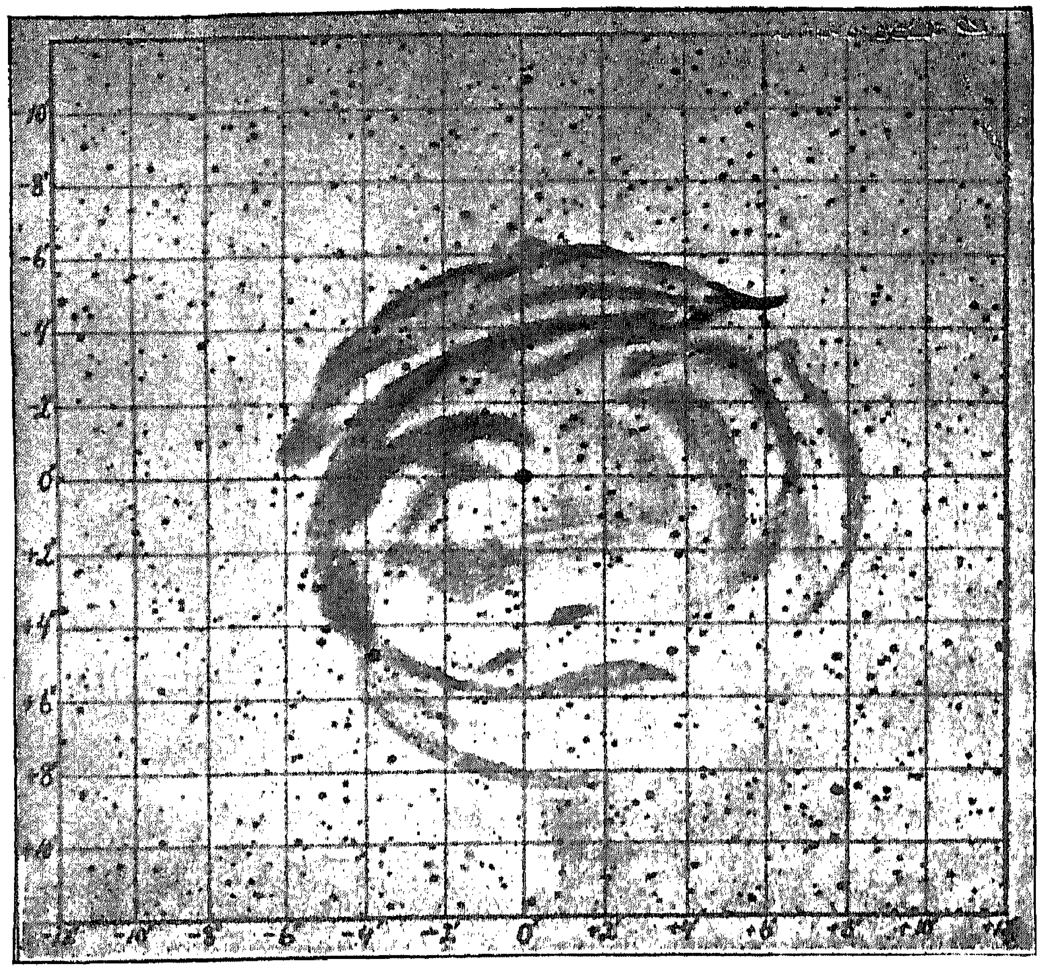
Nova Persei of 1901, both of which were discovered with the naked eye by the same amateur astronomer, Dr. Anderson. Nova Persei has been observed with larger telescopes and spectroscopes, but as far as we know its history is closely like those of previous Novæ. At discovery its magnitude was 2·8, or about the brightness of the seven stars of the Great Bear. The time of discovery was 2 h. 40 m. on the morning of February 22. Twenty-eight hours previously Mr. Stanley Williams photographed the same part of the sky, and although the photograph showed stars fainter than the twelfth magnitude there was no sign of a star in the position Nova Persei afterwards occupied. Thus the light of the star had increased at least 4000 times in 28 hours. Its brightness increased for another day till it became 10 times as bright as at the time of discovery. It then declined till at the end of February it was no brighter than on February 22, at the end of 1901 it was of magnitude 7·0, and at the end of 1902 of magnitude 10·0.

Before the star reached its maximum brightness its spectrum was examined and found to be of the Orion or helium type. The light from the star had passed through an absorbing atmosphere of hydrogen and helium. The next night its character had entirely changed and consisted of bright lines associated with dark lines on the side towards the violet. Some of the bright lines were due to hydrogen and were in the normal position, but the dark lines were shifted

as much as if the absorbing atmosphere which produced them were approaching the Earth with a velocity of 1000 miles a second. In addition a few narrow lines due to sodium and calcium were displaced slightly towards the red. The same displacement was found later when the spectrum had changed, and showed conclusively that the star was moving from the Sun with a velocity of 5 miles per second. The large displacements of the dark lines is most easily explained on the assumption of a great explosion by which hydrogen was driven away from the star with great velocity. The spectrum of the star changed still further till July when the chief nebular line was seen, and in August and September it was very similar to the spectrum of a planetary nebula.

Attempts were made to determine the parallax of the star without success till in the autumn of 1901 Prof. Max Wolf made the surprising discovery that the star was surrounded by a nebula. Professors Ritchey and Perrine of the Yerkes and Lick Observatories obtained photographs by giving long exposures with large reflecting telescopes. Two photographs taken a fortnight apart showed the nebula to be moving. This was clearly shown by comparing the position of the nebula with the stars near it in two photographs taken by Prof. Ritchey. Further photographs led to the conclusion that the surrounding nebula had been expanding continuously since the appearance of the star. A very interesting explanation was given by

Prof Kapteyn. He postulated the existence in space of nebulous matter, stationary and non-luminous. This matter became visible to us by the reflection it



Diag. XCIV.
Nebula surrounding Nova Persei (*Ritchey*)

sent of the light from the Nova. As the light travelling out from the star reached ever widening circles of nebulous matter it illuminated them. More than this, as we know that light travels 186,000 miles a second, it was possible to infer the distance of the Nova from the rate at which the luminous rings spread out. This distance is found to be about 20 million times the

distance of the Earth from the Sun, from which it follows that at its greatest brilliancy Nova Persei was 8000 times as bright as the Sun. By exposing a photographic plate on several nights for 36 hours altogether in a little spectroscope fitted on to a large telescope, Prof. Perrine was able to obtain the spectrum of this faint nebula and found it to be similar to the spectrum of the star in its early stages. In this way it was demonstrated that the nebula shone by reflected light, just as the identity of the lunar and solar spectra could be used to prove that the moon's light is reflected Sun-light.

Only a very hypothetical explanation can be given of the phenomena of new stars. A collision between two bodies is a natural supposition. But the spectroscopic observations do not point to two bodies after the moment of collision. Apparently some conditions have given rise to a great outburst of hydrogen and helium gas from the interior of a star. The possibility of such an outburst is remarkable whatever the exciting cause may have been.

The appearance of such a bright new star as Nova Persei is a very rare phenomenon. The photographs of spectra taken at Harvard College revealed five objects between 1893 and 1899 with the bright and dark line spectrum characteristic of new stars. Probably new stars of small brilliancy are not infrequent occurrences.

CHAPTER XII

THE SIDEREAL UNIVERSE

We have seen in previous chapters what varied knowledge it is possible to acquire about the stars. The distances of a few stars have been determined, and the average distances of large numbers can be approximately fixed. When the distances are known, the velocities can be determined and the luminosities of the stars compared with the Sun. By the study of double stars we are enabled in some instances to determine the masses of stars, and from variable stars the sizes and densities. The spectroscope has taught us something of the chemistry of the stars, and of their temperatures and physical conditions.

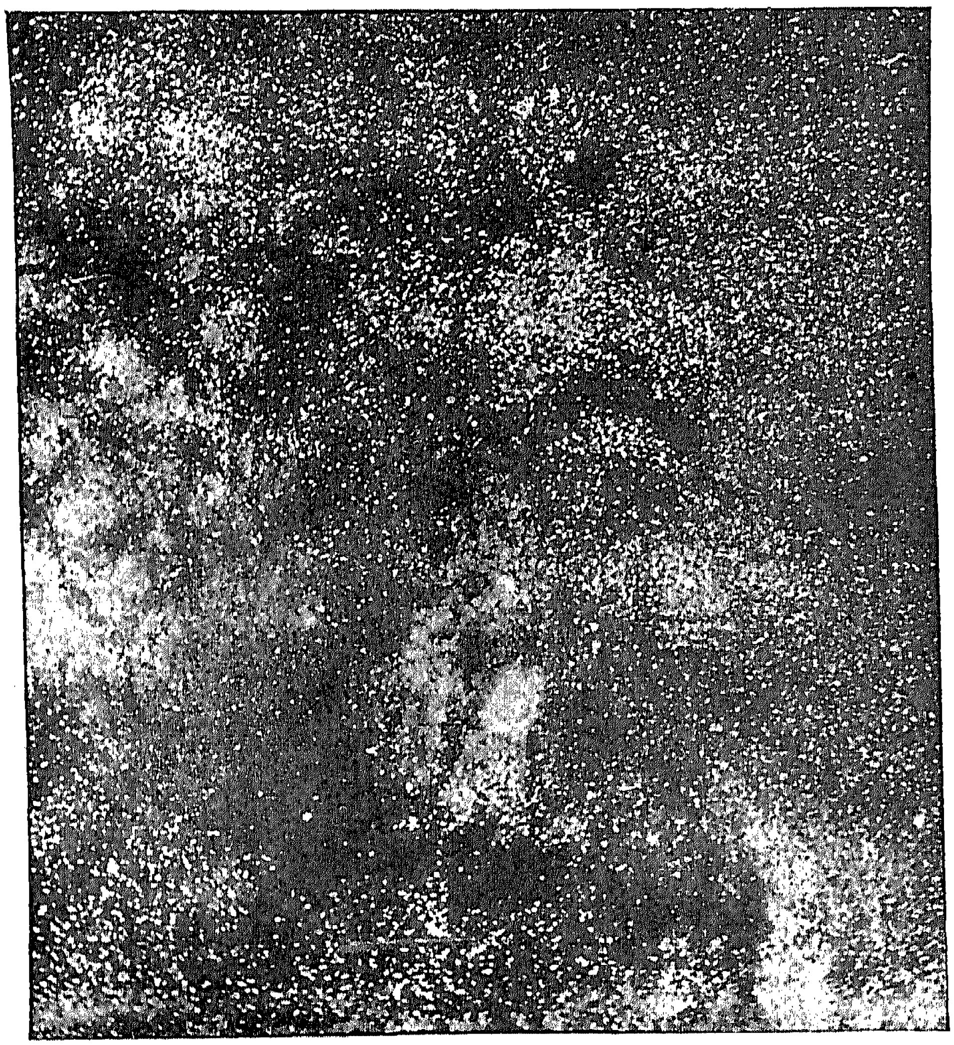
In these different ways the stars are shown to be bodies like the Sun scattered in space at distances apart comparable with 30 or 40 million million miles. The Sun is the body with which we can best compare them. Stars may be much bigger or smaller, denser or much less dense, more or less luminous. Many are double and some triple or quadruple. Planets may circulate round some of them; on this point, however, we have no evidence, but only analogy for a guide.

Sidereal astronomy, as we have seen, is divided

into two branches. One of these concerns itself with the physical state of the stars, and seeks to describe completely these states in the different stages of a star's history, and to follow the life of a star through its whole course. The other branch of sidereal astronomy is of a more geometrical character, and is concerned to describe the universe as it now is, to determine whether it is finite or infinite; if finite, to determine its limits and the number of stars within them; if infinite, to peer as far as possible into its infinity. These two departments cannot be kept entirely separate, as it may, and does, happen that stars of particular kinds or in a particular stage of development have special geometrical relationships. Hydrogen stars, for example, are further from the Earth than those of solar type.

When the stars are looked at as a whole, the most striking feature among them is the existence of the Milky Way, which may be seen on a clear night in winter reaching across the sky as a band of faint light. It stretches right round the celestial sphere, dividing it into equal parts. When examined with a telescope, it is found to be full of stars. The illustration (Diagram XCV) shows part of it as photographed by Prof. Barnard, and brings out the remarkable features of the dark rifts within it, or places void of stars. The Milky Way thus seems to be not one but a number of agglomerations of stars. It certainly contains a vast number of faint stars. Does it also con-

tain bright ones, or are the bright ones apparently in it much nearer to the Sun and merely seen projected against it? An answer can be given to this question by counting the number of bright stars in the dark



Diag. XCV.
Part of Milky Way (*Barnard*).

rifts and comparing the result with the number in an equal area where the faint stars are thick. In this way it is found that a considerable number of bright stars really belong to the galaxy.

The physical characteristics of the stars show some relationship to the Milky Way. Speaking generally, the stars in it are blue, and the remarkable Wolf-Rayet stars are wholly confined to it. New stars, too, usually appear in the Milky Way.

When the number of stars of given magnitudes in different parts of the sky is counted, it is found that the density or number per square degree increases with fair uniformity from the poles of the Milky Way to the Milky Way itself. But this increase in density is much more pronounced for the faint than for the bright stars. If we take stars brighter than 5·5 mag. there are on the average 4·63 in every 100 square degrees near the pole of the Milky Way and 9·07 in the Milky Way itself, or a proportion of 1 : 1·96. For stars of magnitude 8·5 to 9·5 the numbers are 235 and 595, and the proportion 1 : 2·53. For stars of magnitude 11·5 to 12·5 the numbers are 3330 and 15,400, and the proportion 1 : 4·62. The proportion increases very rapidly for higher magnitudes. Moreover, the numbers increase gradually as the Milky Way is approached and do not suddenly alter, as if the Milky Way were entirely distinct from the other stars.

When we consider proper motions, and these are a fair index of the average distances of the stars, it is found that stars of large proper motion are distributed pretty equally in all directions. Prof. Newcomb points out that the number of stars whose proper motion is greater than 5″ a century is no

greater in the Milky Way than at a distance from it. Now in a century the Sun moves a distance equal to 400 times its distance from the Earth, and will therefore produce a movement of $5''$ in a star whose parallax is $\frac{5}{400}''$ or $0{\cdot}0125''$, which corresponds to a distance of 16 million times the Sun's distance. The Milky Way therefore lies beyond this limit. This is to be taken as an example of the method of reasoning, as the numerical result is very far less than the probable distance of the Milky Way.

As the Milky Way divides the sky into equal parts, the Sun is situated in its plane. We do not know how far it may be from the centre, for as yet the distance to the Galaxy in different directions has not been determined. It would seem that the universe of stars extends much further in the direction of the Milky Way than in that perpendicular to it. Its boundary is irregular, but nowhere nearer than 200 million times the Sun's distance. Whether the agglomerations which form the Milky Way are near this boundary, or whether we see some stars which are quite beyond them is as yet unknown. As far as we can tell, the number of stars, though very great, is finite. But there are some indications that light is absorbed in its passage through space, and our conclusions must be very guarded. We are obliged to say with Laplace, "Ce que nous connaissons est peu de chose, ce que nous ignorons est immense."

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THE END